11^{th} IYPT '98
solution to the problem no. 14
presented by the team of Uzbekistan

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Water rise

Immerse the end of a textile strip in water. How fast does the water rise in the strip and what height does it reach? In which way do these results depend on the properties of the textile?

Thanks

Iurevich Iraida for experimental part, Axigendler Boris for help in theoretical analysis.

Overview

- Our solution
- Capillary bounding
- Experimental data analysis
- Conclusions

1 Our solution

To solve this problem we have to investigate the mechanism of liquid rise along the textile and properties of textile influencing the process. Hygroscopic properties are the most important physical properties of textile materials. Being in contact with water materials absorb it by water molecules diffusion into polimer or mechanical capture of water by material's structure. In the last case wetting and capillary bonding play the first role.
Wetting ability of material is defined by chemical nature of fibre, its ability to absorb water and the find of surface, its microrelief and roughness.

2 Capillary bounding

Capillary bounding of water with textile material results from liquid rise along microscopic capillaries ($r < 10^{-5}$ cm), when they put in contact. The degree of capillary absorption of water depends on wetting properties of fibres, their amount and composition, distribution of capillaries in the material's structure. Water in textile materials rises a long capillaries inside the threads, but not between them, because the last have rather great diameter and short length. We observed such motion of water along capillaries in optical microscope with amplification of 50. There we saw threads operating as a system of connected capillaries between the fibres. Water, rising along the capillaries of vertical threads, fills the horizontal capillaries as well. So we concluded that the factor of horizontal threads capillary filling decreases sharply the rate of water rise. And it particularly notirables at the initItals stays.
To investigate different factors with influence on the height and rate of water rising, we carried out experiments with different samples of textiles: cotton print, gauze, staple, silk, wool, mixed textile (viscose with cotton).
This samples differ in:

1. chemical composition and had so different angles of wetting;
2. thread thickness and twisting degree;
3. kind and density of weaving (linen, strengthen, knifed).

Some samples of cotton we thinned out to investigate the weaving density influence on the raising height.

All the samples of textile (of 5 cm width) we graduated by ruler (error in measurement was 1 mm) and the hung up on a stand above the water vessel.
To clemenafe evaporation the samples were covered by polyethylene film. The phenomenon was observed during 7 hours up to visible stop of rising. All the date are represented in tables 1 and 2 and shown in graph 1 and 2.
Graph 1 represents time dependence of height of water rising in different textiles at room temperatures $T = 20°$C, graph 2 the rate of water rising during different time intervals.
All the textiles were examined microscopically and thread thickness and gap width were measured. The results are shown in a table.

3 Experimental data analysis

On the base of experimental data analysis we made the following conclusions:
Threads in textiles really operate as a system of connected capillaries and follow capillary laws. The greatest height is reached in samples of good wetting (samples – cotton, gauze), less one was reached in samples of worse wetting (samples – others). Height of water rising also was influenced by twisting degree. It was defined visually by microscope. This is related with effective radius of capillary and some of them (with too small effective radius) can rise water so long (up to 24 hours), that it's difficult to measure it visually.
Experiments with thinning out the material shown it that weaving dencity influence only the time of rising, but not the height. In the case of knifed weaving (mixed material with horizontal fibres) water practically doesn't rise because here all woven capillaries directed in transversally.

t in min	cotton print	c.p. rarified	gauze	staple	silk	wool	mixed along	mixed across
10	6	9	11.5	3.6	3.8	0.7	0.2	8.2
20	9	11.8	16	4.9	4.7	1.2	0.4	10.3
30	15.2	18	18	6.2	5.4	1.7	0.5	12.0
40	16.5	19.8	19	6.8	6.0	2.2	0.6	13.3
50	18.3	21.2	20.2	7.3	6.5	2.8	0.7	14.1
60 (1h)	20	22	21.2	7.9	6.9	3.3	0.7	14.7
70	20.5	23.5	22.8					
80	21	24	23.5					
90	22	25	24	8.4	7.2	3.7	0.8	15.3
100	23.5	25.5	24.5					
110			26					
120 (2h)	26.2	28	27	8.7	7.4	4.0	0.9	15.7
130			28.5					
140			30					
150	28.2	31.8	31	9	7.5	4.1	1.0	15.9
180 (3h)	30.5	34	34	9.2	7.5	4.1	1.0	15.9
210	32.5	36.5	36	9.2	7.5	4.1		
240 (4h)	34	37.5	36.5					
270	35	38	37					
300 (5h)	36	39	37.5					
330	36.6	39.5	38					
360 (6h)	37.2	40	38.5					
390	38	40	39					
420 (7h)	39	40						
480 (8h)	40	40						

Table 1: Height of water rising in different textiles (in cm)

t in min	cotton print	c.p. rarified	gauze	staple	silk	wool	mixed along	mixed across
10	0.6	0.9	1.1	0.36	0.38	0.07	0.02	0.82
30	0.46	0.45	0.33	0.13	0.08	0.05	0.015	0.19
60	0.16	0.13	0.11	0.06	0.05	0.05	0.007	0.09
90	0.07	0.1	0.09	0.02	0.01	0.013	0.003	0.02
120	0.14	0.1	0.09	0.01	0.007	0.01	0.003	0.013
180	0.07	0.1	0.1	0.008	0.0017	0.002	0.002	0.01
240	0.06	0.06	0.04	~ 0	~ 0	~ 0	~ 0	

Table 2: Rate of water rising during different time (in $\frac{\text{cm}}{\text{min}}$)

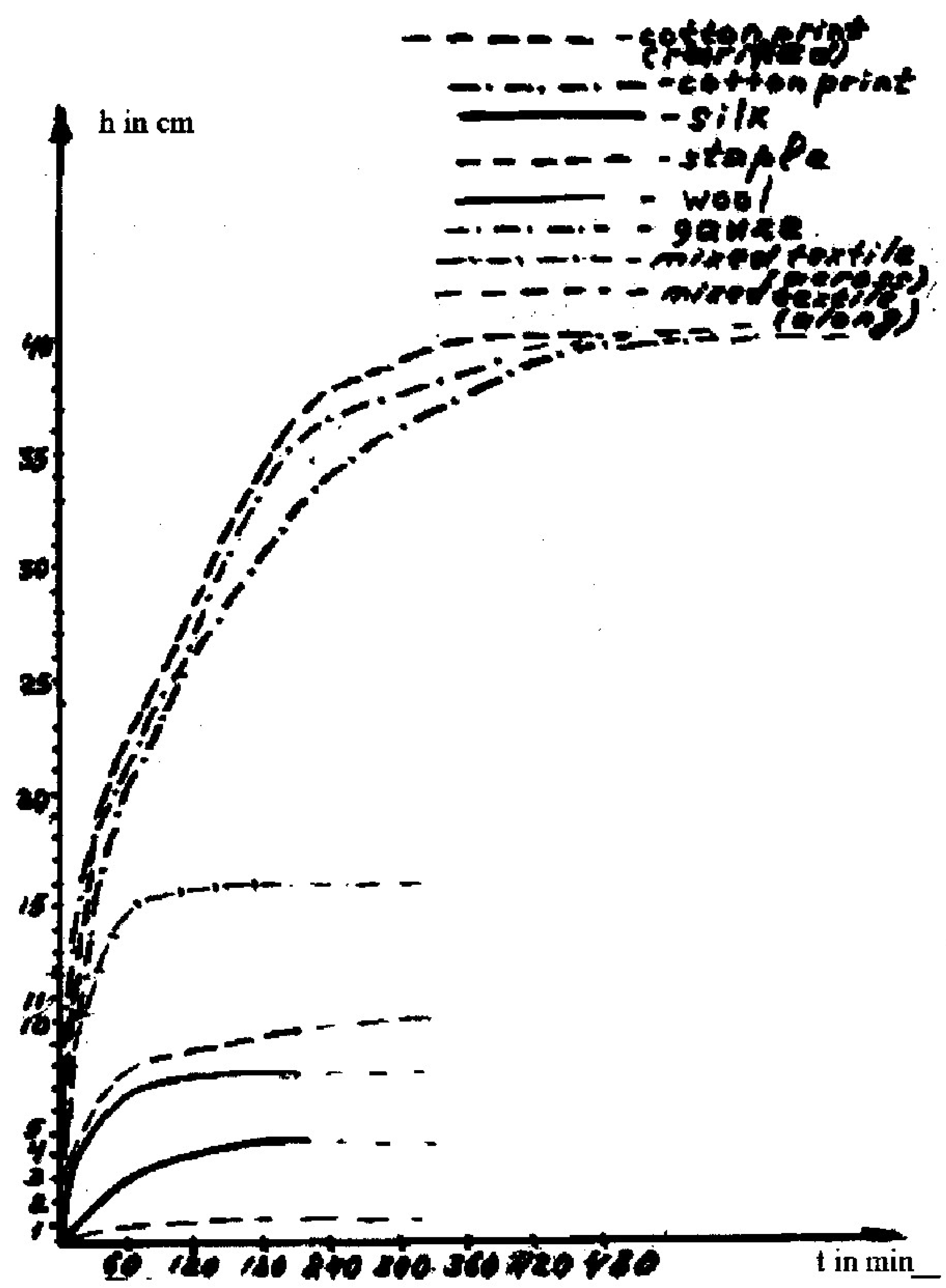

Figure 1: Height of water rising

So we generalised the experience and proposed the following model. We consider a thread as ideal capillary and so we can show the following equations:

$$F_\sigma = F_\eta + P \tag{1}$$

where
- F_σ is force of surface tension,
- F_η is resistant force due to liquid viscosity,
- P is weight (force of gravity).

These forces expressions are

$$F_\sigma = p \cdot S \tag{2}$$

where
- p is pressure,
- S is area of surface in capillary cross section.

$$F_\eta = 2 \cdot \Pi \cdot \eta \cdot h \cdot V \tag{3}$$

where
- η is dynamical viscosity factor,
- V is velocity,
- h is height.

Substitution of these forces into (2) gives the expression for velocity.

$$V = \frac{dht}{dt} = \frac{\sigma Rc}{\eta h} - \frac{R_c^2 c \rho g}{2\eta} \tag{4}$$

Now lets consider the special cases

1. when the velocity is equal to zero, the maximum height of water rising in capillary is

$$h_0 = \frac{2\sigma}{\rho g R_c} \tag{5}$$

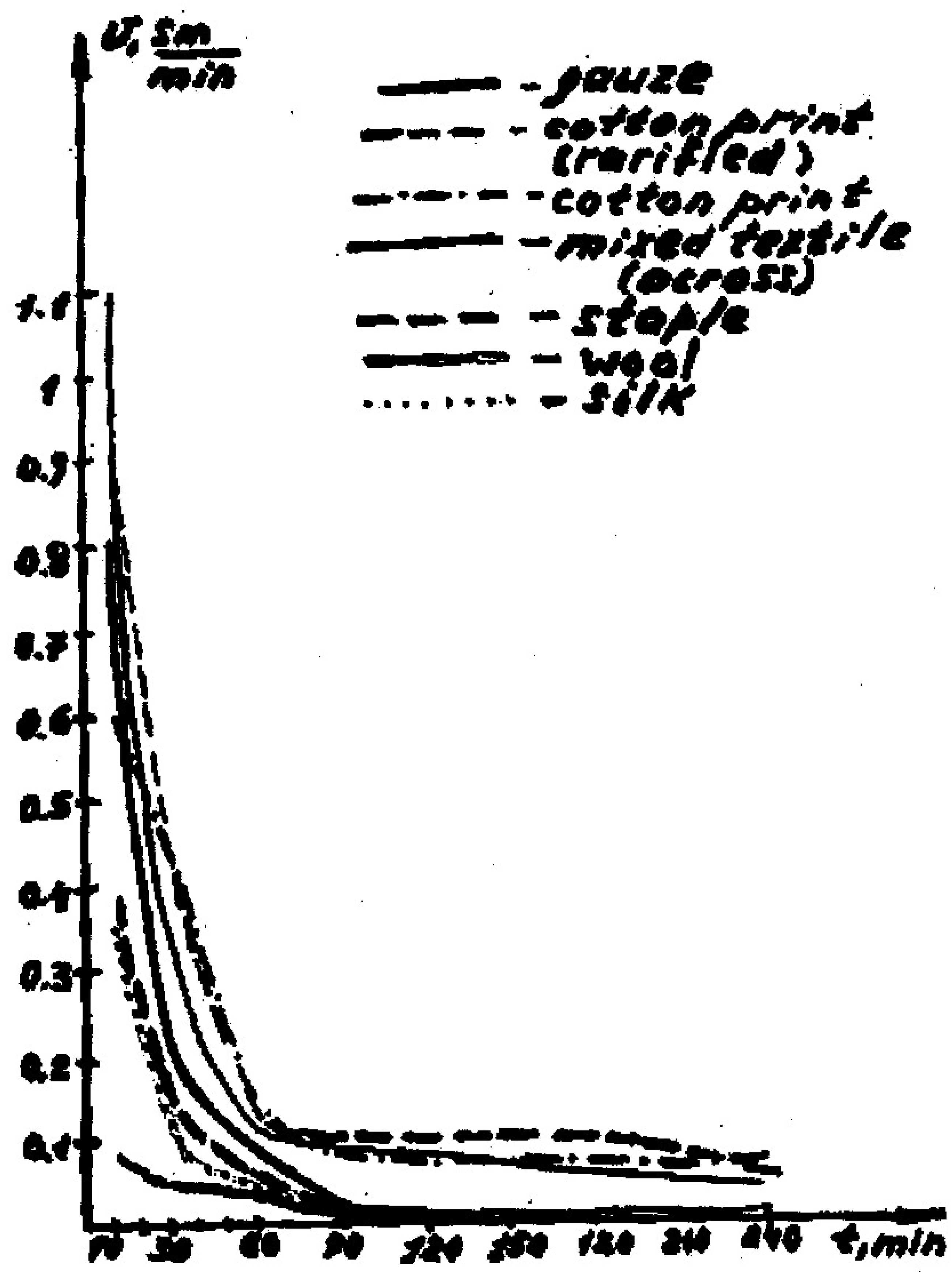

Figure 2: Velocity of water rising, (free cells were not mesured. Calculation of the speed by: $v = \frac{h_{i+1}-h_i}{t_{i+1}-t_i}$)

2. if $h_0 \gg h_t$ the height of water rising during short time interval is

$$h_t = \sqrt{\frac{2\sigma R_c t}{\eta}} \tag{6}$$

3. if $h_t = h_0$ then

$$t_0 = \frac{2\sigma\eta}{R^3\rho^2 g^2} \tag{7}$$

Substitution of experimental height values into (5) and (7) gives effective radius of capillary for gauze equal $R_c = 38\,\mathrm{mc}$ and $t_0 = 30\,\mathrm{s}$.
Experimental and estimated values of time don't coincide with one another that shows the mechanism of water flow in textile to be more complicated one and the model of ideal capillary is not quite correct here.
So the notable difference in estimated and experimental results can be explained by the following factors that are difficult to be taken into account in the mathematical model.

1. Calculations consider the case of ideal wetting (when angle $\angle Q \to 0$) whereas the real wetting angle is variable value for different samples.

2. Water moves along the system of connected capillaries of different radius.

3. It's impossible to take into account some technologically properties of textile – density, kind of weaving, twisting degree and so on.

4. All the factors mentioned above influence sufficiently the height and rate of water rising in textile, that was proved experimentally.

Figure 3: Various textiles

4 Conclusions

But still our theoretical model describes the phenomenon rather correctly.
Our experiments were limited by real time of observation (that is the time of visible change of velocity), while rising time may be more long because capillaries in the thread are of different radius and in some of them with small radius the height is rather great.