

Modeling of liquid flow in surface discontinuities

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Abstract. Polymer composite and metallic materials have found wide application in various industries such as aviation, rocket, car manufacturing, ship manufacturing, etc. Many design elements need permanent quality control. Ensuring high quality and reliability of products is impossible without effective nondestructive testing methods. One of these methods is penetrant testing using penetrating substances based on liquid penetration into defect cavities. In this paper, we propose a model of liquid flow to determine the rates of filling the defect cavities with various materials and, based on this, to choose optimal control modes.

1. Theory

High quality and reliability of products made of metal and non-metallic materials cannot be provided without effective modern methods of nondestructive testing used at all stages of the production cycle: design, manufacture, operation and repair. The defects in structures made of different materials can be detected by means of acoustic, radiation (X-ray), thermal, radio wave, optical, electrical and other methods of nondestructive testing, including liquid penetrant test [1, 2].

Liquid penetrant testing techniques are based on the ability of liquids to penetrate into the cavities of defects. These techniques can be employed to detect all types of surface closed-end and open-end discontinuities, such as cracks, delaminations and leaks in products of any non-porous material, including ferrous and non-ferrous metals, glass, ceramics, plastics and other materials. The hydrodynamics of the liquid flow in capillaries obeys the equations for a Newtonian liquid with a reasonable degree of accuracy. A colored or fluorescent liquid used in penetrant testing to ensure the quality of products is referred to as penetrants. These liquids are typically based on various alcohols and kerosine [3–5].

When liquids fill open-end capillaries, capillary absorption occurs, i.e. wetting forces rise the liquid to a certain height h above the surface. The filling of the closed-end capillary with liquid differs from that of the open-end capillary since the entrapped air-vapor mixture limits the penetration depth. Thus, the process involves two stages that are fundamentally different in physical nature. At the beginning, when the liquid gets into contact with the surface discontinuity (microscopic rupture of the surface), it penetrates rapidly deep into the defect to a certain depth h under the impact of capillary forces. However, the process then slows down substantially as the capillary pressure increases. The first stage ends when the capillary pressure of the liquid approaches the pressure of the air-vapor mixture. Then the second stage begins. The capillary stage of filling changes into the diffusion stage, when the gas compressed in the defect cavity gradually dissolves in the liquid and diffuses towards the defect mouth [6,7].



A problem of practical interest is to reveal the patterns of the filling of closed-end and open-end capillaries by various liquids and to determine the limiting depth of capillary filling and the time of liquid penetration to this depth.

This paper provides the result of the modeling of liquid flow in open-end and closed-end capillaries with flat and parallel walls. A differential equation of liquid flow in the capillary is obtained with respect to its slope, surface roughness, regions with different wetting parameters, an analytical change in the size of the gap in different regions under the assumption of the liquid flow close to a laminar one:

$$h_1'' + \frac{1}{h_1} (h_1')^2 + \frac{8\mu(r, r_a)}{r^2(h_1)\rho} h_1' - \frac{2\sigma(h_1)a(h_1)\cos(\theta_s(h_1))}{r(h_1)\rho h_1} + \frac{P_a}{\rho(h_0 - h_1)} + g \sin(\alpha) = 0,$$

where $h_{0,1}$ is the total and instantaneous capillary depth, θ_s is contact angle, a is roughness coefficient, σ is surface tension, P_a is atmospheric pressure, μ is dynamic viscosity, r_a is the radius of the penetrant macromolecule (if dimensional effects are taken into account), α is the angle of inclination of the capillary, g is gravitational acceleration, and ρ is liquid density. This equation takes into account the dependence of the dynamic shear-viscosity coefficient of the penetrant during reduction or expansion of the capillary radius (allows for dimensional effects through the procedure). The equation enables modeling of absorption with allowance for a continual change in all the parameters of the problem.

To simulate liquid flow in closed-end and open-end capillaries, a software package is developed to perform the numerical solution of the differential equation obtained. The interface of the package for computer simulation of the liquid flow is shown in Figure 1.

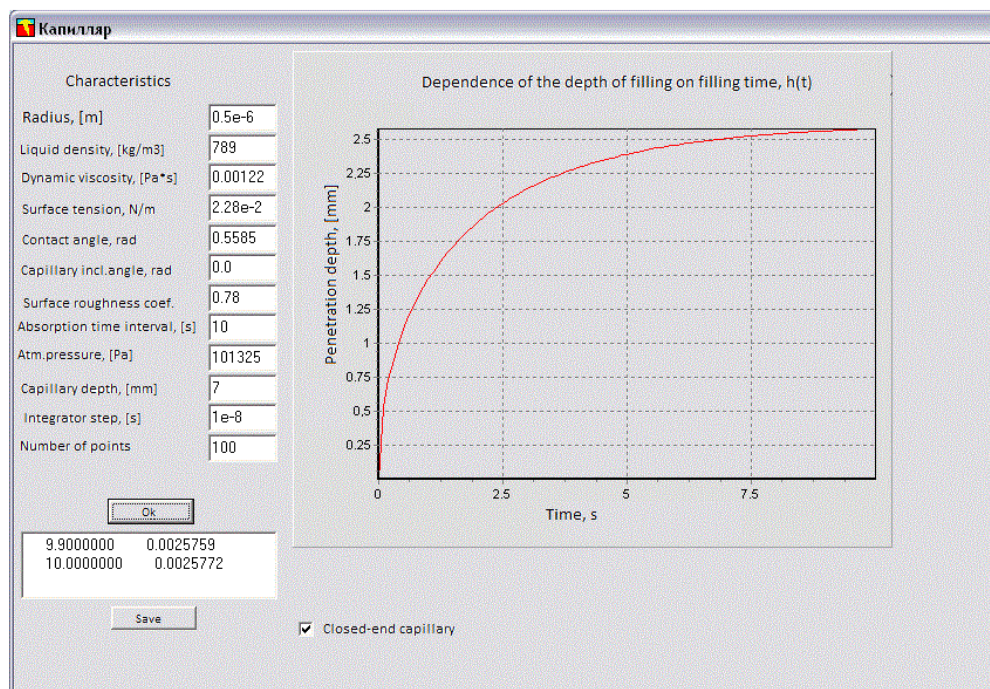


Figure 1. Interface of the package for computer simulation of liquid flows.

The windows to enter the parameters are displayed on the left side. These parameters fall into two groups. The first group is related to the geometric and material parameters of the model. The second group includes the calculation parameters and graphical interpretation of the results.

The first group involves the following parameters:

- liquid density (kg/m^3);
- dynamic viscosity (Pa s);
- surface tension (N/m);
- contact angle (rad);
- capillary inclination angle relative to the horizontal (rad);
- surface roughness coefficient (dimensionless value determined by the ratio of rough and smooth surface areas);
- absorption time interval (s);
- atmospheric pressure (Pa);
- capillary depth (mm). It should be noted that this parameter comes into operation if the mode "Closed-end capillary" is chosen. Otherwise, the program will perform the calculations for an open-end capillary.

The second group includes the following parameters:

- integrator step (s). Despite the fact that the method automatically selects the integration step, it is desirable to set its initial value at the start. This is due to the fact that the differential equation refers to the category of stiff equations and has a singularity for the point $h=0$;
- number of points on the graph. This parameter is required to reduce the modeling results on a common graph during variation of the problem parameters. Otherwise, automatic selection of the integration step generates the resulting files of different lengths.

An output field for intermediate results can be found in the lower left corner. This field is a simplified text editor with the ability to view all intermediate values and operate them if required. This editor comprises two columns – the current time value and the sorption depth.

2. Model experiments:

To construct a mathematical model of the liquid flow in open-end and closed-end slot-like capillaries. The capillary dimensions of the chosen samples made of glass and aluminum were as follows: widths of 10, 7, 5 and 3 μm , and depths of 10.0, 7.0, 5.0, 3.0, 1.0 and 0.3 mm. Kerosine and alcohol described in [3–5] as the main common components, as shown in Table 1, of flaw detection materials were used as penetrants.

The contact angles measured by the droplet detachment method (A.O. Osipov, O.P. Osipov, I.I. Gogonin) are presented in [8].

Table 1. Summarizes the values of the basic equation parameters.

Liquid	Dynamic viscosity coefficient, $\text{Pa}\times\text{s}, 10^{-3}$	Surface tension coefficient, $\text{N/m}, 10^{-3}$	Contact angle, deg		Liquid density kg/m^3	Surface roughness	
			Aluminium	Glass		Aluminium	Glass
Kerosine	1.85	24.00	37	25	820	0.78	1.0
Alcohol	1.22	22.80	32	17	789		

The observation time for all the experiments was chosen to be equal. During that time, the liquid filled the capillary to a certain depth.

The results of modeling the flow of the liquids (alcohol and kerosine) in the slot-like capillaries were interpreted graphically. Figure 1 shows that the rate of filling the open-end capillaries with liquids is inversely proportional to their opening width, that is the narrower the capillary, the longer it takes for the liquid to travel to the same depth. Figures 2 and 3 illustrate the dependencies of the liquid penetration depth on the filling time for an aluminum-alcohol pair with a capillary width of 5 μm . For all other material-liquid pairs, the graphs appeared to be similar.

When filling closed-end capillaries with liquids, the filling depth is limiting. The graph presented in Figure 2 shows that the limiting depth of filling closed-end capillaries is about 10% of the total capillary depth.

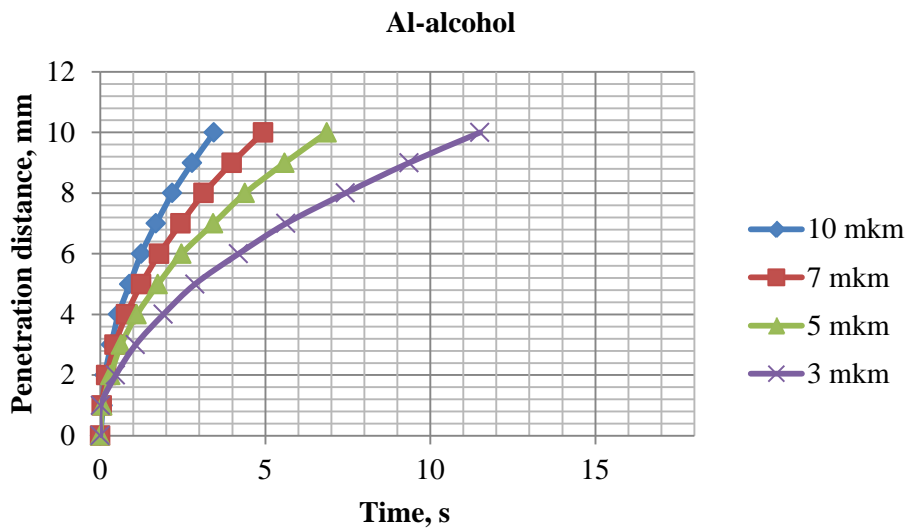


Figure 2. Dependence of the depth of filling a slit-like capillary on filling time (open-end capillary).

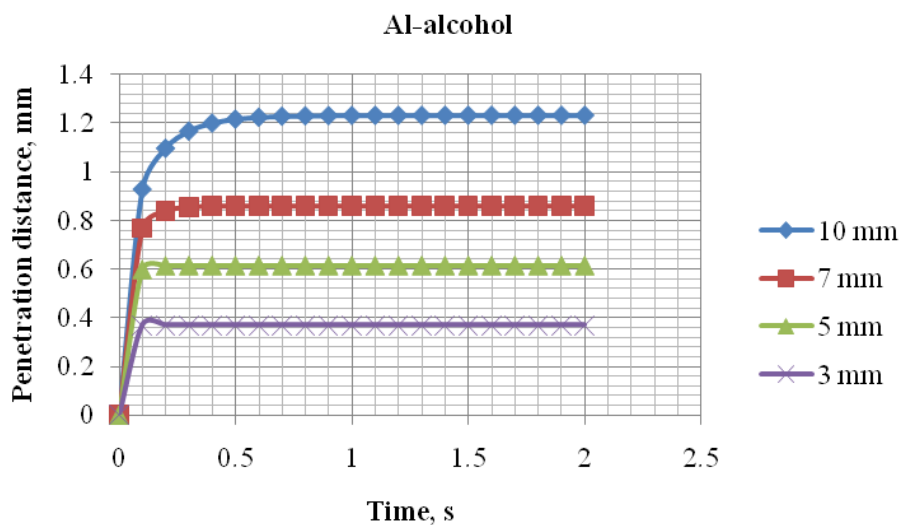


Figure 3. Dependence of the depth of filling a slit-like capillary on filling time (closed-end capillary).

Figures 4 and 5 show the results of modeling the flow of liquids (alcohol and kerosine) in open - and closed-end capillaries with a 5 μm opening made of aluminum and glass on filling time. The speed of flow of alcohol in the slit-like capillary is higher than that of kerosine. The speed of liquid flow in products made of non-metal is higher than that in metal materials.

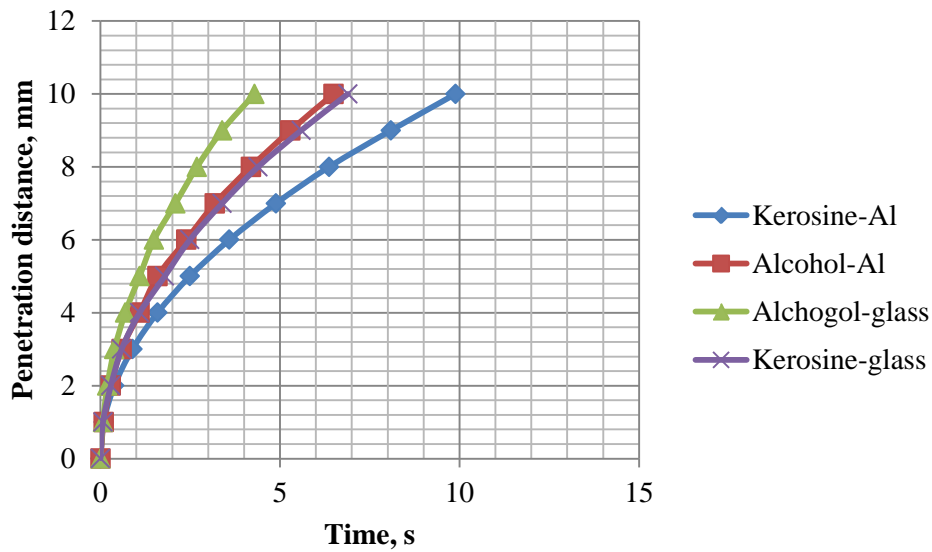


Figure 4. Dependence of the depth of filling a slit-like capillary on filling time (open-end capillary) for material-liquid pairs.

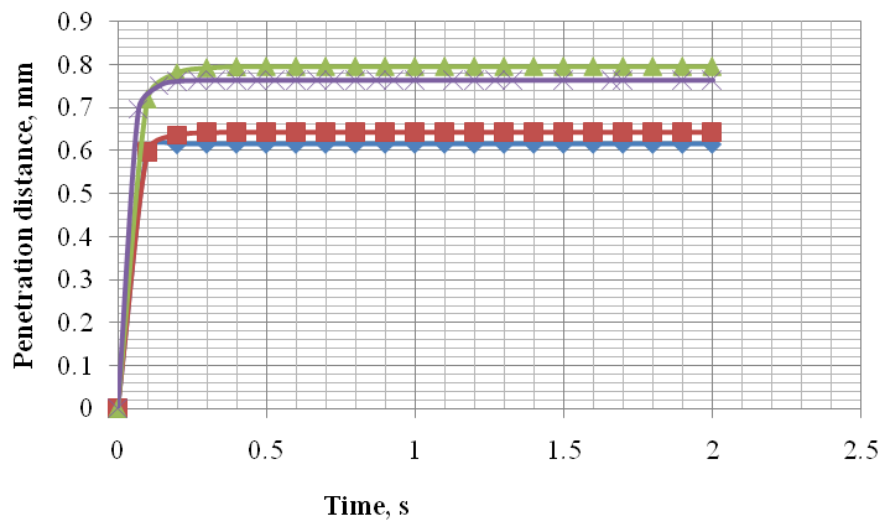


Figure 5. Dependence of the depth of filling a slit-like capillary on filling time (closed-end capillary) for material-liquid pairs.

3. Conclusion

Thus, the graphs show that the rate of filling glass capillaries with liquids is higher than that of filling aluminum capillaries. Numerous model experiments on other types of materials proved the necessity to take into account all the model parameters to construct the quality control procedures for products. However, it should be noted that the time required for sorption of capillaries in a number of polymeric and nonmetallic materials is slightly less than that for metals. The reduced time of capillary sorption accelerates penetrant testing.

References

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