Modeling the Filament Formation in the Wet Spinning of Synthetic Fiber from Polymer Solutions

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Abstract-A mathematical model is proposed for gelation that takes place as the coagulant diffuses into polymer solution filaments. Gelation kinetics is modeled numerically. The manner in which the size of the complete gelation zone varies with time is determined and analyzed. A comparison is made between experiment and calculation. Drawing upon the model, the dependence of gelation time on basic process variables is estimated.

INTRODUCTION

Basically, the wet spinning of synthetic fiber includes pumping the starting polymer solution through spinnerets, and then passing the filaments thus produced through a coagulating bath. As the polymer solution passes through the bath, the coagulant finds its way into the polymer filaments and accumulates there. When enough of the coagulant has accumulated, the polymer solution is separated into a solid (gel-like) and a liquid phase. The gel-like phase is the primary structure of the fiber and governs its properties in many respects. Optimization and control of the spinning process, especially when various types of fiber need to be spun, are complicated operations which require a great effort and highly skilled personnel to perform. To enhance the reliability and speed of their action, it is essential to have an adequate model of gelation, that is, of the first stage in fiber spinning [1]. Many investigators have attempted to develop such models [1-7]. Unfortunately, all of their models fail to take into account some important aspects of the structuring process, such as the phase equilibrium of the polymer-solvent-coagulant system, the temperature behavior of the kinetics, the kinetics of phase separation, relaxation processes, etc.

Existing models of wet spinning [1-7] fail to estimate the kinetics of structuring, that is, to establish the pattern of changes in the thickness of the solidified polymer with time. $R_g(t)$ of the gelation zone changes with changes in process variables. A model that considers the kinetics of gelation is proposed in

[8], but it is based on far too many assumptions. The aim of this paper is to develop a model for the initial stage of fiber spinning (filament formation) from a polymer solution by the wet spinning process, using existing models and taking into account the phase equilibrium of the polymer-solvent-coagulant system, heat transfer, the evolution of diffusion processes with temperature, the existence of a layered two-phase structure when filaments are formed from a polymer solution, the thermal effects associated with the reactions of the components involved in the process, and changes in fiber size in the process.

THE MODEL

In developing the model, we make the following assumptions about filament formation. (1) The problem is treated under axial symmetry in a one-dimensional statement, assuming that the coagulant diffuses solely along the radius in the absence of convection and that the fiber is an unbounded cylinder whose radius is small in comparison with the length of the coagulating bath. (2) Only the diffusion of the coagulant and solvent is considered, assuming that the polymer does not diffuse into the coagulant. (3) The diffusivity of the coagulant into the polymer solution, D_1, differs from its diffusivity into the solidified gel-like layer, D_0, being in the ratio $D_0 = D_1/3$ [1], and both are functions of temperature, $T(r, t)$. (4) Mass transfer occurs under boundary conditions of the first type, assuming that, during the complete gelation time, the coagulant concentration in the bath at the fiber changes not more than 3% [2] at a solution filament velocity of about 0.1 m/s. (5) During gelation, the gel layer shrinks uniformly across its entire thickness. (6) The thermophysical coefficients of the polymer solution and of the solidified layer are functions of the temperature $T(r, t)$ and are independent of the coagulant concentration $C(r, t)$; heat transfer at the fiber surface obeys Newton's law, that is, third-kind boundary conditions. (7) We neglect the change in the filament radius caused by mass transfer between the filament and the coagulating bath, and by the extension of the filament. (8) We consider the formation of only one filament in the coagulating bath and neglect any interaction between filaments.

Keeping in mind the rationale of the wet spinning process and the data from [1-8], we will consider the diffusion of the coagulant into the fiber and of the coagulant from the fiber into the coagulating bath. The applicable equation of diffusion in cylindrical coordinates takes the form

$$\frac{\partial C_i}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}[D_i(T)r\frac{\partial C_i}{\partial r}] \tag{1}$$

This is a system of four mass transfer equations that describe the diffusion of the coagulant into the polymer solution for $i = 0$ and into the gel for $i = 1$, and the respective diffusion of the solvent for $i = 2$ and 3. Heat transfer in the fiber is described by the equations

$$\frac{\partial T_j}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}[a_j(T)r\frac{\partial T_i}{\partial r}]+q_v \qquad (2)$$

This is a system of two equations for $j = 0$ in the case of the polymer solution and for $j = 1$ in the case of the gel. The initial conditions at $t = 0$ are

$$T_j(r, 0) = T_{nj}(r). \quad C_i(r. 0) = C_{ni}(r). \qquad (3)$$

The boundary conditions are as follows. At the outer boundary of the fiber, that is, $r = R$

$$-\lambda(T)\frac{\partial T_0(R_0,t)}{\partial r} = \alpha[T_0(R_0,t) - T_s(t)]\Big|_{r=R_0}, \qquad (4)$$

$$C_i(R_0,0) = C_{si}(t), \quad i = 0,2,$$

at the polymer solution-gel interface, that is, $r = R$

$$D_i(T)\frac{\partial C_i(r,t)}{\partial r} = D_{i+1}(T)\frac{\partial C_{i+1}(r,t)}{dr}, \qquad (5)$$

$$C_i(R,0) = C_{i+1}(t). \quad i = 0,2,$$

$$\lambda_1(T)\frac{\partial T_1(r,t)}{\partial r} = \lambda_0(T)\frac{\partial T_0(r,t)}{\partial r} \qquad (6)$$

$$T_1(R,t) = T_0(R,t)$$

At the center of the fiber, that is. $r = 0$, the symmetry conditions take the form

$$\frac{\partial T_1(r,t)}{\partial r} = 0\Big|_{r=0}, \frac{\partial C}{\partial r} = 0\Big|_{r=0}, \quad i = 1,3. \qquad (7)$$

The heat source in equation (2) accounts for the heat released upon mixing the coagulant and the solvent [12], and its power is

$$q_v = \frac{q_m}{G}\frac{\partial C}{\partial t} \qquad (8)$$

Gelation causes a change in the volume [3] and geometrical dimensions of polymer solution filaments. The change comes about because the gel takes up a smaller volume than does the polymer solution. The fiber thickness is a variable, $R_o = R_0(t)$, and can be found from the equation

$$R_0^2 \ (t) = R^2(t) + \gamma \ [R_0^2 \ (0) - R^2 \ (t)]. \tag{9}$$

The presence of a movable boundary poses additional difficulties in solving the problem. One way to change from a no stationary to a stationary boundary is to use the von Mises transformation [9], which introduces a new dimensionless variable, η, defined as $\eta = r/R_0(t)$. The change from the original independent variables r and t to the new ones η and t is done, using the expressions

$$(\frac{\partial}{\partial r})_{r,t} = \frac{1}{R_0(t)} \frac{\partial}{\partial \eta}$$

$$\tag{10}$$

$$(\frac{\partial}{\partial t})_{r,t} = (\frac{\partial}{\partial t})_{\eta,t} - \eta A \frac{\partial}{\partial \eta}$$

Upon the change of variables and after some algebraic manipulations, equations (1) through (8) take the form

$$\frac{\partial C_i}{\partial t} = \frac{1}{\eta R_0^2} \frac{\partial}{\partial \eta} [D_i(T)\eta \frac{\partial C_i}{\partial \eta}] + \eta A \frac{\partial C_i}{\partial \eta} \tag{1a}$$

$$\frac{\partial T_j}{\partial t} = \frac{1}{\eta R_0^2} \frac{\partial}{\partial \eta} [a_j(T)\eta \frac{\partial T_1}{\partial \eta}] + \eta A \frac{\partial C_i}{\partial \eta} + q_v \tag{2a}$$

$$T_j(\eta,0) = T_{nj}(\eta), \quad C_i(\eta,0) = C_{ni}(\eta) \tag{3a}$$

For $\eta = 1$

$$-\frac{\lambda(T)}{R_0}\frac{\partial T_0(1,t)}{\partial \eta} = \alpha[T_0(1,t) - T_s(t)] \tag{4a}$$

$$C_i(1,0) = C_{si}(t) \qquad i=0,2$$

For $\eta = R/R_0$

$$D_i(T)\frac{\partial C_i(\eta,t)}{\partial \eta} = D_{i+1}(T)\frac{\partial C_{i+1}(\eta,t)}{\partial \eta} \tag{5a}$$

$$C_i(\eta) = C_{i+1}(\eta), \qquad i=0,2$$

$$\lambda_1(T)\frac{\partial T_1(\eta,t)}{\partial \eta} = \lambda_0(T)\frac{\partial T_0(\eta,t)}{\partial \eta} \tag{6a}$$

$$T_1(\eta,t) = T_0(\eta,t)$$

For $\eta = 0$

$$\frac{\partial T_1(\eta,t)}{\partial \eta} = 0 \quad \frac{\partial C_i}{\partial \eta} = 0 \tag{7a}$$

$$q_v = \frac{q_m}{G}\left(\frac{\partial C}{\partial t} - \eta A \frac{\partial C}{\partial \eta}\right) \tag{8a}$$

In what follows, we will use the original independent variables r and t to make the presentation more instructive, and the new variables η and t will be used in solving equations (1a) through (8a).

In calculating changes in the gelation front with time, $R(t)$, it is necessary to consider the phase separation diagram of the three-component polymer-solvent-coagulant system. It establishes the conditions for phase separation (gelation).

The gel thickness is found from the transcendental equation

$$C_0[R,t] = C_{cr}[T(r,t)], \tag{11}$$

where C_{cr} is found from the phase diagram. This equation is solved for the gelation front coordinate $R = R(t)$. Then the present gel thickness $R_g(t)$ can be defined as $R_g(t) = R_0(t) - R(t)$. Using this relation and equation (11), we are in a position to find the gel thickness as a time function, $R_g(t)$.

We solve the nonlinear system of equations (1) through (11), using an implicit finite-difference scheme [9, 10]. The von Mises transformation does not complicate the task. The algebraic system of equations is linearized by an iterative method [10], which takes no more than three iterations steps. Iterations are used because the behavior of $R_o(t)$ is not known in advance and has to be determined in the course of the solution. To see if it is correct, the numerical solution is checked against known solutions to linear problems from [11], and in the case of nonlinear problems, against a check example from [10]. With the chosen parameters of the numerical scheme, the error is not greater than 1.5%.

For numerical simulation, we choose the soft type of wet spinning, using the polyacrylonitrile (PAN)-dime-thyl formamide (DMF)-water system. The initial concentrations in the solution are 20% PAN and 80% DMF, and in the coagulating bath, 80% DMF and 20% water. The process variables are $R_0(0) = 0.05$ mm at $t = 0$, $T_n = 50°C$, and $T_s = -10°C$.

The heat and mass transfer coefficients are chosen as follows. According to [3], the diffusivity of the coagulant into the solution varies with temperature, so we choose it to be $D_1 = (2.2 + 0.0475T) \times 10^{-10}$ m^2/s, and that of the solvent into the solution, $D_3 = 1,4D_1$. The diffusivity into the solidified polymer is assumed to be $D_i = D_{i+1}/3$, $i = 0.2$ after [1]. The coefficients necessary to solve the thermal problem involving the PAN-DMF solution are borrowed from [12], neglecting their temperature dependence: $\lambda = 0.2$ $W/(m\ K)$, $G = 2100$ $J/(kg\ K)$ and $\rho = 950$ kg/m^3. For lack of data on the thermal properties of the gel, we assume them to be the same as for the polymer solution. The value of $\alpha = 1000$ $W/(m^2\ K)$ is determined after [1].

The contribution due to the heat of mixing, equation (8), to the heat defined in equation (2) is estimated to be such that can cause a change in temperature no more than 0.5% of the filament temperature range for the system in question and under the spinning conditions chosen, given the same order of magnitude for the time derivatives of temperature, concentration, and specific heat of mixing, q_m, of water and DMF [13].

The kinetics of gelation is calculated using the phase diagram for the PAN-DMF-water system from [14].

A graph relating the thickness of the solidified polymer (gel) to time, $R_g(t)$, is shown in Fig. 1. This is an 5-shaped curve implying that at the start of the process the thickness R_g is proportional to the square
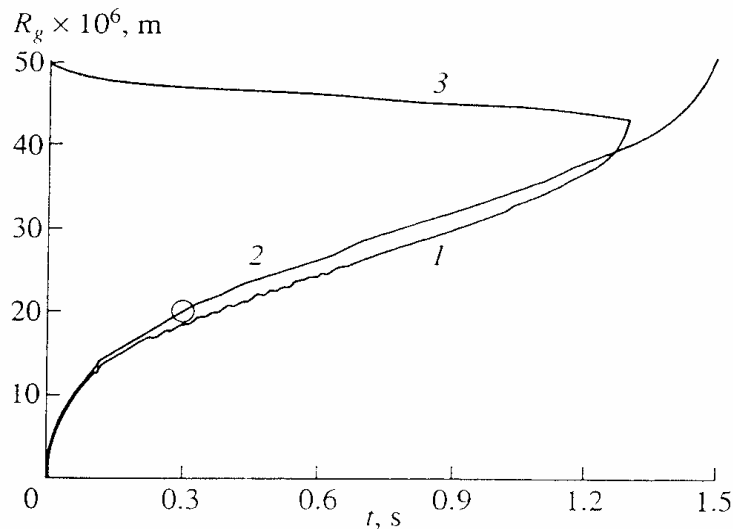
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Fig. 1. Gel thickness as a function of time, $R_g(t)$. *(1)* For $R_0(t)$; (2) for R_o = const; *(3)* filament thickness as a function of time, $R_0(t)$.
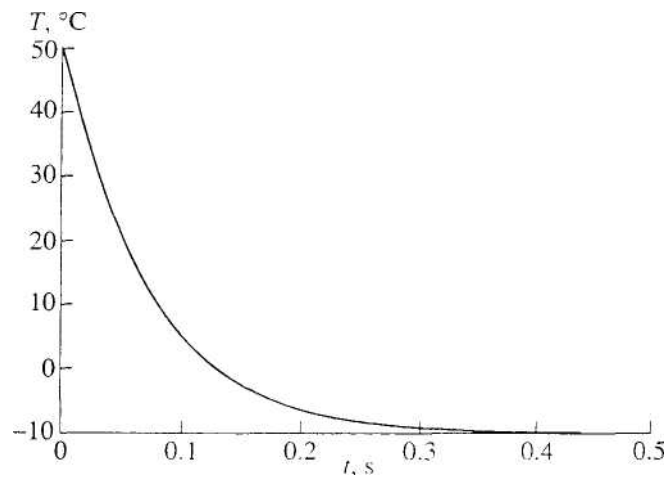

Fig. 2. Fiber temperature averaged over radius as a function of time.

time, $(t)^{1/2}$, then it turns almost linear, and. as time passes, it becomes proportional to a higher power of time. In the subsequent calculations, we assume that $R_0 = R_0(0)$ = const. This assumption does not cause a qualitative change in the behavior of the relations given below, but makes them more illustrative.

We calculate how the temperature of the fiber varies with time. The results are given in Fig. 2. Note that the fiber cools to ambient temperature in 0.4 s. which is about one-quarter of the gelation time.

Figure 3 illustrates the manner in which the coagulant concentration in the fiber varies with coordinate, and Fig. 4, with time. The kinks in the curves reflect the fact that at time t the gelation front is positioned at a point whose coordinate is $r(t)$. The kinks are traceable to discontinuities in the

concentration gradients and to the conservation of coagulant mass fluxes boundary
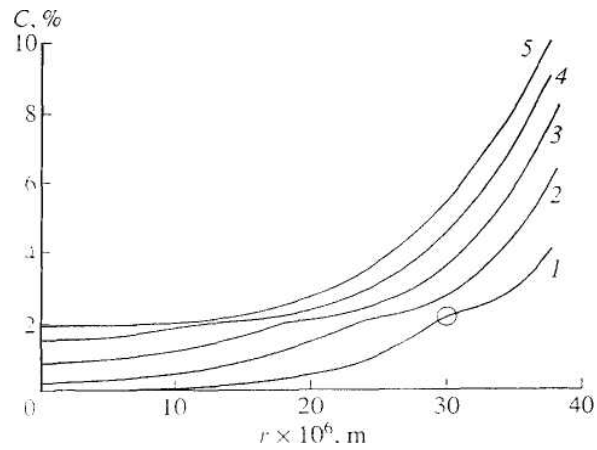

Fig. 3. Distribution of coagulant concentration along radius at different instants .r: *(1) 0.3; (2) 0.6; (3) 0.9; (4) 1.2;(5) 1.5 s.*
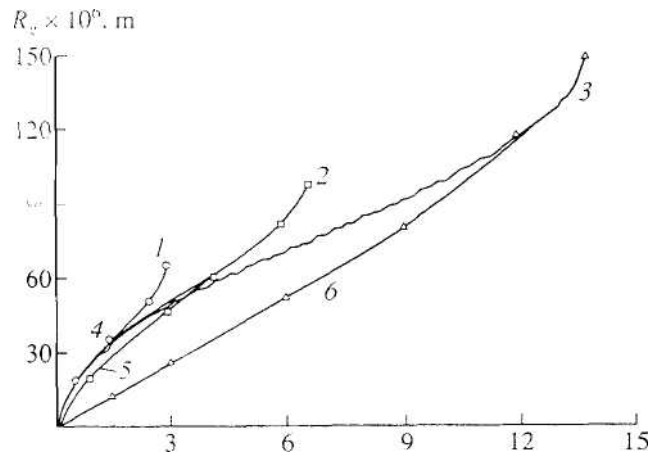

Fig. 4. Coagulant concentration in fiber plotted against time at points with coordinates *r. (1)* 0; (2) 0.00001; (3) 0.00002; (4)0.00003 m.
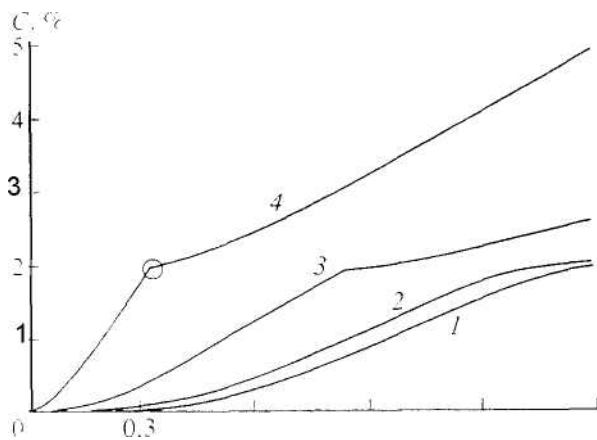

Fig. 5. Gel thickness plotted against time. $R_g(t)$.*(1)* Through *(3)* calculation; *(4)* through (6) experiment [2]; *(1)* and *(4)* for $R_0 = 0.07$ mm: (2) and *(5)* R_0 - 0.105 mm; *(3)* and (6) $R_0 = 0\,15$ mm

conditions of the fourth kind, equation (5)]. To illustrate the fact, a point is highlighted in Figs. 1, 3, and 4, which tells us that at time $t = 0.3$ s the solidification front is positioned at a coordinate $R = 0.03$ mm, which corresponds to a gel thickness $R_g = 0.02$ mm.

To see if the proposed mathematical model is workable and gives a close fit to the actual situation, we compare the calculated results with the experimental data from Mezhirov [15] for PAN fibers wet-spun from an aqueous rhodanide polymer solution. Mezhirov [15] reports his observations of changes in the gelation radius with time, $R_g(t)$, for different spinneret radii. In his experiments the filament radius was $R_0 = 0.15, 0.105$, and 0.07 mm. the initial temperature was equal to that of the coagulant in the bath (isothermal conditions), $T_n = T_s = 11°C$, the coagulant (water) concentration in the bath was $C_0 = 90\%$, and the initial polymer solution concentration was $C_n = 42.68\%$. All the water, free and bound, was taken to be the coagulant.

In numerical simulation based on the proposed model, we use the phase diagram for the aqueous rhodanide solution [14], For calculations, we need to know the diffusivity of the coagulant into the polymer solution, D_1, and the diffusivity of the coagulant into the polymer gel, D_0. We borrow them from experimental data reported in [15]. For a filament radius $R_0 = 0.105$ mm, the numerically fitted diffusivity is $D = 2.2 \times 10^{-10}$ m^2/s for a ratio $D_0 = D_1/3$. This value assures a close fit between the experimental and calculated complete gelation time, t_g - 6.8 s. Using this value of diffusivity, we then calculate the manner in which the radius of the solidified polymer varies with time, $R_g(t)$, for filaments differing in R_0. The calculated results are presented in Fig. 5. A good fit with the experiment can be seen for two curves and a satisfactory fit for a filament of radius $R_0 = 0.15$ mm. Note also agreement in the complete gelation time, in the qualitative behavior of the 5-shaped curves, and in the time variations of R_g. The discrepancy between the calculated and the experimental data may have arisen because the mathematical model is developed under several assumptions, and because there may be some inaccuracies in the phase diagram used in the calculations [14].

The most crucial point in the wet spinning of synthetic fibers is the buildup of the polymer shell (gel) over time. Therefore, our next task is to analyze the pattern of changes in the gelation zone size with time, $R_g(t)$, and to explain why this function is S-shaped. To this end, we consider an approximate linear model for gelation, expressed in the form of algebraic equations. In doing so, we assume that a simplified nonlinear model will preserve the qualitative form of the function $R_g(t)$. This assumption is based on the following fact. The nonlinearity, which makes it possible to calculate the kinetics of gelation, causes the diffusivity to change with time and space only quantitatively. Therefore, we are in a position to take into account the changes that occur in the diffusivity of the solution and the gel as the gel region undergoes dynamic changes.

The gel thickness is found from the transcendental equation (11). The proposed gelation model will

transform into the linear equation of diffusion for an unbounded cylinder on the proviso that (1) the spinning operation goes on under isothermal conditions; that is, the initial temperature of the polymer solution is the same as that of the coagulating bath, so that the filament temperature remains constant, $T(r, t) = const$; (2) the coagulant has the same diffusivity into the polymer solution and into the gel; (3) the coagulant has a constant diffusivity. If these conditions are satisfied, equation (11) is simplified to the form

$$C_i[R, t] = C_{cr} = const. \tag{12}$$

A similar approach to the linear equation of diffusion is proposed in [6].

For comparison, consider solving equations (11) and (12) for the "'soft" spinning operation in the case of the PAN-DMF-water system. To facilitate the comparison, we assume that the spinning variables have the same values as they had in the previous case, with minor changes necessitated by the fact that the operation goes on isothermally (the initial temperature of the solution is the same as that of the bath, $T_n = T_s = -10°C$). In the circumstances, the concentration corresponding to polymer gelation in the phase diagram at the specified temperature is $C_{cr} = 2\%$ after [14]. We take it that the diffusivity of the coagulant into the fiber, averaged over temperature and time, is $D = 2.08 \times 10^{-10}\ m^2/s$.

In the case of a linear model, the total gelation time can be found, using the tabulated solution of the linear problem at the center of a cylinder, $r = 0$, given in [11]. To demonstrate, the gelation may be taken to have reached completion when at the point most distant from the filament surface, which is the fiber center, the coagulant concentration is sufficient to bring about the phase transition of the polymer solution to a gel, or when $C_i(0, t) = C_{cr}$. For this value of C_{cr}. the total gelation time is $t_g = 1.03\ s$. This estimate is as much as one-third smaller than the calculated time $t_g = 1.5\ s$ (see Fig. 4). The reason is that a linear model is unable to take into account the changes that occur in the diffusivity upon gelation.

The solution to equation (12) on the time interval $[0, t_g]$ is represented by curve 1 in Fig. 5. In the same figure, curve 2 gives the solution obtained, using the gelation model. Comparison of the solidified polymer thickness as a function of time found from the model, equations (1) through (11), with the solution of a similar linear equation of diffusion (1) shows that both behave similarly in qualitative terms. Therefore, in the subsequent discussion we take it that the results obtained from an analysis of the function $R_g(t)$ for the linear problem qualitatively explain the kinetics of gelation in the case of the nonlinear model as well.

Resort to a linear model does not significantly simplify equation (12)-it remains transcendental. Therefore, in order to transform equation (12) to an algebraic equation and to further analyze the behavior of gel thickness with time, we use a well-known method for analysis of solutions to the parabolic equation of transport from [16]. It is based on an approximate solution of a given transport process at short and long times. In this method, the gelation time t_g is divided into two parts. The point of division is the value

of the Fourier number $Fo_n = Dt_n /R^2_o = 0.081$, corresponding to the instant when changes begin in the concentration at the cylinder's center $r = 0$, that is, the point farthest from the filament's surface, or the coagulant source. To demonstrate, for D the value of Fo_n, corresponds to $t_n = 0.97\ s$. This is the instant where the concentration at the fiber's center is 1 %, which checks with the assumptions made. In [16], it is proposed that in the first half-interval, where $t < t_n$, the concentration should be calculated, using an approximate expression, which is an exact one for a semi-infinite medium [11,16]. In the second half-interval, where $t > t_n$, this should be done, using a different approximate solution, which is the first term of an infinite series (solutions to the linear equation of diffusion for an infinite cylinder [11,16]). We can then obtain expressions for the polymer gelation thickness in explicit form as a function of time for a certain critical concentration C_{cr} as

$$R_g(t) = (Dt/[erf^{-1}\{\theta\}])^{1/2}, \qquad for \quad 0 < t < t_n, \tag{13}$$

where erf^{-1} is the inverse of the error function erf, $\theta = (C_{cr} - C_s)/(C_n - C_s)$, and

$$R_g\{t\} = R_0\{1 - [1 - \{\theta\}exp(5.79(Fo-Fo_1))]^{1/1.51}\} \tag{14}$$

for $t_g > t > t_n$.

The results calculated by equations (13) and (14) are given in Fig. 6. They agree closely with the solution of the nonlinear problem for $t < t_n$ and satisfactorily for $t > t_n$. It is noteworthy that both calculated curves are in full qualitative agreement with the function $R_g(t)$ derived earlier and explain its S-shape in qualitative terms. Equations (13) and (14) imply that.

$$t_g = R_o^2[Fo_1 - ln(\theta)/5.79]/D = t_n + t_{cr} \tag{15}$$

where θ ranges between 1 and 0. Therefore, it is obvious that $ln(\theta) <= 0$. Equation (15) may be written as a sum in which the first term t_n is the time required for the coagulant concentration at the center of a filament, $r = 0$, to change by about 1% relative to the initial value. In other words, the coagulant stream has reached the filament's center, or the point farthest from the fiber's surface. The time t_{cr} is the time during which the coagulant concentration changes from its original value to the value required for gelation, C_{cr}, at a given temperature. With such an approach, the gelation process may
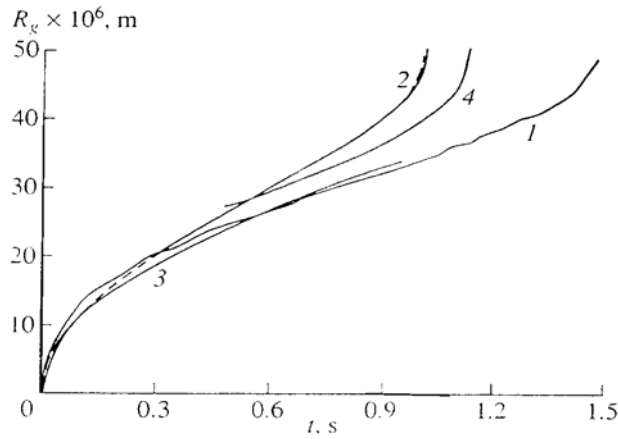
Fig. 6. Gel thickness plotted against time. Rg(t): (l) after (11); (2) by equation (12): (3) by equation (13); (4) by equation (14).
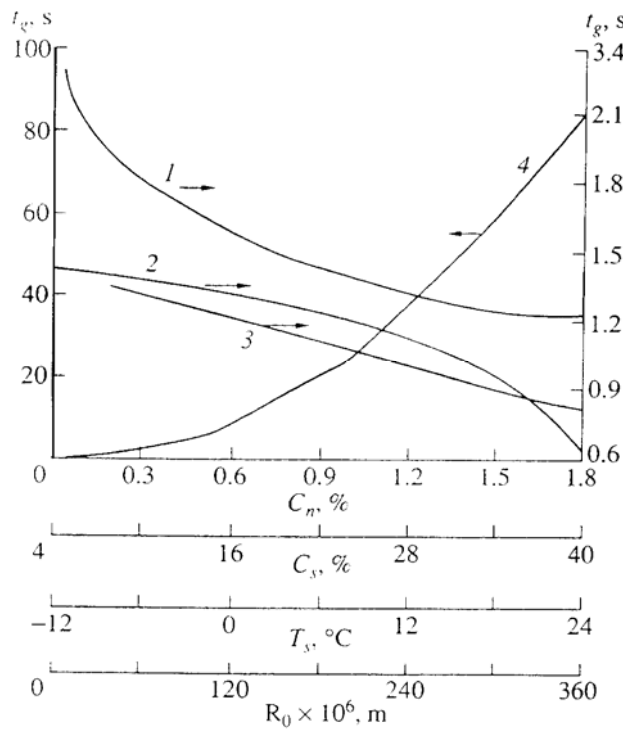

Fig. 7. Complete gelation time t_g plotted against fiber-spinning variables: *(1) coagulant concentration in bath C_s: (2) coagulant concentration in polymer solution C_n, (3) bath temperature T_s; (4) polymer solution filament radius R_o.*

be thought of as proceeding in two stages whose duration is t_n and t_{cr}, respectively.

It is of practical interest to analyze the way the gelation characteristics behave with changes in the wet spinning process variables. The basic variable that characterizes the solidification of the polymer is the complete gelation time t_g Given a constant fiber velocity v, the time t_g determines the bath length

$$L=vt_g. \tag{16}$$

Figure 7 gives graphs of the complete gelation time t_g plotted against the wet-spinning process

variables, such as the coagulant concentration in the bath C_s, the coagulant concentration in the polymer solution C_n, the temperature of the solution in the bath T_s, and the radius of a polymer solution filament R_0. The range of the variables is chosen to be close to what actually occurs in practice. The results are derived, using our mathematical model for the "soft" wet spinning process in the PAN-DMF-water system. During a simulation run, one of the variables is changed and the remaining ones are held constant. Interestingly, the curve of the total gelation time plotted against fiber radius is a quadratic parabola. This fact confirms the possibility of using relations of the type (15).

CONCLUSION

In this paper, we have come up with a model for gelation in the wet spinning of synthetic fibers from polymers. In contrast to its previous counterparts [1-7], it makes possible the computation of gelation kinetics on the basis of a phase diagram, the joint heat and mass transfer from the movable interface, and mass transfer coefficients as functions of temperature. The model and the associated computer software can also come in useful in calculating wet spinning variables for other polymer solutions.

ACKNOWLEDGMENTS

NOTATION

$$A = \frac{1}{R_0}\left(\frac{\partial R_0}{\partial t}\right);$$

$a(T)$-thermal diffusivity;

$C(r, t)$-concentration;

C_{cr}-coagulant concentration at the instant of the phase transition at temperature T;

$C_p(r, t)$-approximate solution of the linear problem of diffusion;

D-diffusivity;

erf - error function;

erf^1 - inverse (of the) error function;

G - specific heat;

q_m - heat of mixing per unit mass of coagulant;

q_v - heat of mixing per unit volume of coagulant;

$R_o = R_0(t)$ fiber radius coordinate varying with time

from $R_0(0)$ to $R_0(t_g)$;

$R = R(t)$ - gelation front coordinate varying with time from R_0 to $r = 0$;

$T(r, t)$ - temperature at time t at point with coordinate r;

T_n - initial temperature of polymer solution;

T_λ - coagulating bath temperature;

t_g - complete gelation time;

v - fiber velocity in coagulating bath;

α - heat transfer coefficient;

γ - volumetric contraction coefficient of polymer upon gelation;

λ - thermal conductivity;

p - density;

$\theta = (C_{cr} - C_s)/(C_n - C_s)$;

$\eta = r/R_0$;

Bi - Biot number;

Fo - Fourier number.

SUBSCRIPTS

$i = 0,1$ for coagulant; $i = 2, 3$ for solvent;

$i = 0,2$ *for $R_0 > r > R$;*

$i = 1,3$ for $0 < r < R$:

$j =$ for $R_0 > r > R$;

$j = 1$ for $0 < r < R$;

n - initial value of a quantity;

s - value of a quantity at fiber surface, in coagulating bath;

k - k-th time interval in numerical solution;

cr - value of a quantity at a phase transition;

g - quantities pertaining to the polymer gel;

l - quantity derived from solving a linear problem;

p - approximate solution of a linear diffusion problem.

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