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# Determination of the Activation Energy During Drawing of Optical Fibers

Modelling of drawing of optical fibers and capillaries from glass preforms is usually reduced to the treatment of quasi one-dimensional models of flow of a Newtonian fluid, it's viscosity strongly dependig on temperature. This is usually presented by an Arenius type relation [1]:

(1) $$\mu=\mu_0 exp[(U/(G.T)] ,$$

where $\mu$ is the viscosity of the vitreous mass, $\mu_0$ is a pre exponential factor, U is the activation energy of the glass viscous flow, G is the gas constant and T is the temperature of the vitreous mass. This relation describes well the behaviour of the silicate glass under arbitrary low temperatures which correspond to the real technological process [1], [2]. The activation energy depends on the glass chemical composition and its determination is to be done for every case under consideration.

The scheme of drawing of micro capillaries is shown in Fig.1. However, a quasi onedimensional model of the process is given in [3]. It is derived in a cylindrical coordinate system, using an approximate analytical solution, the latter being obtained disregarding surface, inertia and gravity forces, as well as slope and curvature of the capillary average surface. This solution has the form:

- in the heating region

(2) $$\bar{R}=\bar{h}=1-(1-m).exp[\theta(\bar{T}-1)]$$

(3) $$x=-\frac{T_P.\rho c_P Q}{q_1 R_0}\left\{\bar{T}-\bar{T}_0-\frac{1}{\theta}ln\left[1-(1-m)exp[\theta(\bar{T}-1)]\right]\right\}.$$

- in the cooling region

(4) $$\bar{R}=\bar{h}=m-(E^{-1/2}-m)\left\{exp[\theta(\bar{T}-1)]-1\right\},$$

(5) $$x=l-\frac{T_P.\rho c_P Q}{q_1 R_0}\left[\frac{q_2}{q_1}\right]^{-1}E^{-1/2}\ \mathrm{x}$$

$$\mathrm{x}\left\{\bar{T}-1-\frac{1}{\theta}ln\left\{m^{-1}E^{-1/2}-(m^{-1/2}E^{-1/2}-1)exp[\theta(\bar{T}-1)]\right\}\right\}$$

The link between the capillary average radius during drawing and the velocity in the corresponding cross section along the axis x in the two regions, is given by

(6) $$\bar{V}=\bar{R}^{-2},$$

while the parameter m is determined as

(7) $$m=R_P/R_0.$$

In the above expressions R, h, V and T denote average surface radius, wall thickness and absolute temperature in the corresponding cross section, respectively. Indices 0 and 1 are related to the cross sections $x=0$ and $x=L$, where by L is denoted the length of the transition region where drawing is performed. This region is formally divided into two parts by the cross section where the temperature of the formed capillary is maximum - $x=l$, and the radius of the middle surface is $R_P$. The region of heating corresponds to $0\leq x\leq l$, while the region of cooling - to $l\leq x\leq L$. The heating and the cooling fluxes in the cross section $x=l$ are denoted by $q_1$ and $q_2$. These fluxes have no strict physical meaning and can be treated as parameters of the solution. The dimensionless average radius, wall thickness, velocity and temperature are denoted by $\bar{R}=R(x)/R_0$, $\bar{h}=h(x)/h_0$, $\bar{V}=V(x)/V_0$, $\bar{T}=T(x)/T_P$ p and $\theta=U/(G.T_P)$.

The relations for the maximum temperature $T_P$ and the corresponding coordinate $x=l$ are as follows:

(8) $$T_P=\frac{U}{2G\,ln(m)}+\left[\frac{U^2}{4G^2ln^2(m)}-\frac{U}{G\,ln(m)}\left[T_0-l\frac{q_1 R_0}{\rho c_P Q}\right]\right]^{1/2},$$

(9) $$l=-\frac{T_P\rho c_P Q}{q_1 R_0}\left[1-\frac{T_0}{T_P}-\frac{1}{\theta}\,ln(m)\right] .$$

The preform temperature in the cross section $x=0$ is denoted by $T_0$ in relations (8) and (9). The temperature $T_1$ of the capillary formed at the furnace exit for $x=L$ is expressed by

(10) $$T_1=T_P\left\{1-\frac{1}{\theta}\,ln(m^{-1}E^{-1/2})-\frac{(L-l)q_1 R_0}{T_P\rho c_P Q E^{1/2}}\,\frac{q_2}{q_1}\right\} .$$

The parameter E in relations (2)-(10) expresses the link between drawing and feeding velocity - $E=V_1/V_0$, while $Q=RhV=const.$

The maximum temperature $T_P$ of the formed capillary and the corresponding coordinate $l$ can be previously given in a number of cases. This allows for the use of an analytical solution in order to find R(x), h(x), V(x), and T(x), whereas an additional iteration procedure for the calculation of $q_1$ and $q_2/q_1$ can be employed. Moreover, it is supposed that the activation energy from the viscosity relation (1) is known. However, non standard silicate glass is often used in practice for optical fiber drawing, where the energy value is unknown and is to be taken from literature.

In what follows a method for the determination of the activation energy is proposed using the analytical solution. However, a simple experiment is performed on a real production line for optical micro capillary drawing and the energy is directly determined, without the employment of a special laboratory equipment.

The results from the analytical solution allow to determine the outer surface of the formed capillary in the heating region, the latter being bounded by cross sections $x=0$ and $x=l$:

(11) $$S=2\Pi\int_0^l\left[R(x)+0.5h(x)\right]dx .$$

The variable x can be substituted by T for convenience. This can be done by introducing R(x) and h(x) in rel.(11) through rel.(2), since the function x(T) is given in rel.(3). In this case the integration boundaries are from $T_0$ to $T_P$. Thus rel.(11) yields

(12) $$S=-\frac{\rho c_P Q}{q_1 R_0}\,2\Pi(R_0+0.5h_0).(T_P-T_0) .$$

The sign "-" in rel.(12) is due to the fact that flux $q_1$ is directed against the external normal to the outer surface, i.e. $q_1<0$ . It can be easily obtained from rel.(12) that

(13)
$$\frac{\rho c_P Q}{q_1 R_0} = - \frac{S}{2\Pi(R_0+0.5h_0).(T_P-T_0)} .$$

The above expression can be substituted in rel.(9) and the equation thus obtained can be solved with respect to $\theta$, the latter being reduced to

(14)
$$\theta = ln(m).\frac{T_P.S}{(T_P-T_0').[S-2\Pi l(R_0+0.5h_0)]} .$$

It is easily seen that, owing to rel.(7), the expression for $ln(m)$ can be reduced to:

(15)
$$ln(m) = ln\left[\frac{R_P+0.5h_P}{R_0+0.5h_0}\right] ,$$

where the notation $h_P = h(l)$ is used. In fact $R_0+0.5h_0$ and $R_P+0.5h_P$ are the external radii of the drawn capillary in cross sections $x=0$ and $x=l$ respectively.

Using the definition for $\theta$, given above, and the expression (15), we can obtain an expression for the activation energy, related to the gas constant, i.e.

(16)
$$\frac{U}{G} = ln\left[\frac{R_P+0.5h_P}{R_0+0.5h_0}\right] \frac{T_P^2.S}{(T_P-T_0).[S-2\Pi l(R_0+0.5h_0)]} .$$

The right hand side of expr. (16) includes quantities which can be considerably easily determined from experiments. Their values can be introduced in this relation and thus the activation energy of the viscous flow of the vitreous mass can be calculated. Such an experiment can be performed on a machine for drawing of micro glass capillaries from tubular preforms.

The maximum absolute temperature $T_P$ to which the specimen is heated along the furnace length, and the distance $l$ from the beginning of the furnace to the specimen cross section, where the temperature $T_P$ is measured, can be determined. All this can be done when a steady process with a constant feeding and drawing velocity is established, and a stabilized heat exchange in the furnace is attained - Fig.1. The furnace is switched off when $T_P$ , $T_0$ and $l$ are measured, the process is interrupted and the specimen is taken out of the furnace. Then its radius $R_P$ for a cross section at a distance $l$ from the beginning of the furnace (Fig.1), as well as the geometry characteristics of the capillary outer surface S, are measured. The activation energy for a unit gas constant is calculated according to formula (16).

Experiments for the determination of glass activation energy, without previously knowing the glass chemical composition, are performed on a laboratory installation for drawing of optical fibers and capillaries. The used specimens are tubes of silicate glass with outer diameter $10{,}5.10^{-3}$ m and wall thickness $10^{-3}$ m. The experiments are performed for: feeding velocity $V_0=2{,}5.10^{-5}$ m/s ; draw rate ratio E=478.51, length of the formed capillary L=0,3 m .

We give results from two experiments, for different heating conditions. The measured values of the outer diameter of the formed capillary are plotted in fig.2. They are obtained for: $T_0=638$ K, $T_P=1003$ K, $l=0{,}16$. The activation energy, calculated by using expr. (16), is U/G=43369 K. Data for $T_0=673$ K, $T_P=1103$K and $l=0{,}15$m are given in Fig.3. The activation energy for a unit gas constant is determined as U/G=44927 K.

The temperature is measured during the drawing process by using thermo couples, and the diameters - after taking out the specimen and using a microscope. The results from the analytical solution are plotted for comparison by a dense line in Fig.2 and Fig.3. They are obtained for U/G=44000 K , $\rho=3000$ kg/m$^3$ - glass density, $c_P=1000$ J/kg.deg - thermal capacity. The obtained data for the activation energy are in agreement with the data given in [1].

The results, obtained in the paper, can be used for expressing the glass viscosity relation when modelling drawing of optical fibers and micro capillaries, and for the design of technological processes. The proposed method can be applied either on laboratory equipment, or on production installations.

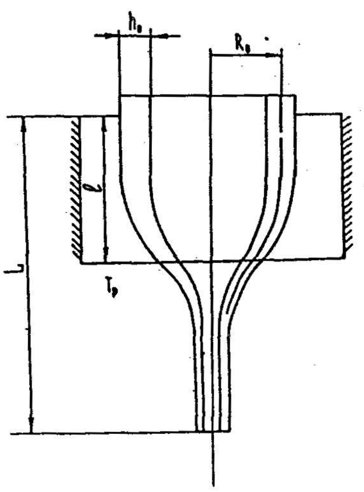

Fig.1

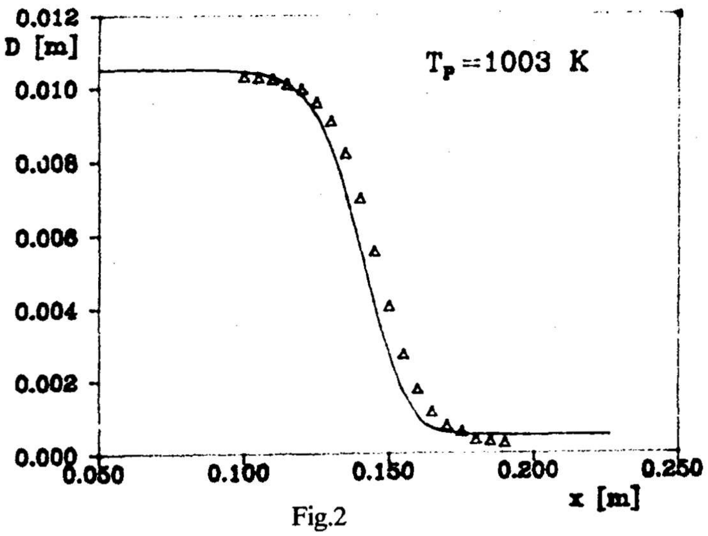


Fig.2

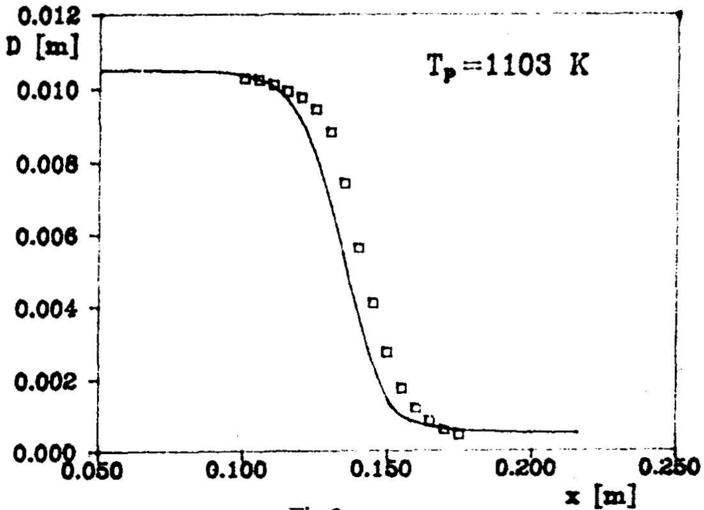


Fig.3

R e f e r e n c e s

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