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On the Fåhræus-Lindqvist Effect in the Blood Motion in Small Vessels

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Abstract

The article analyzed the motion of the blood in narrow capillary vessels by using the microscopic behavior of the solid-fluid interaction. The Fåhræus-Lindqvist effect (or sigma effect) is related to the blood flow through vessels of less than 0.3 mm diameters. The effect was observed in living systems and in mechanical, non-biological suspensions like salt solutions.

Keywords

Solid-Fluid Interaction, Capillary Vessels, Fåhræus-Lindqvist Effect

1. Introduction

The Fåhræus-Lindqvist effect explains the decreasing of the viscosity of the blood with decreasing of the vessel tube radius. This behavior was observed in vessels with small radius since the years 2002 [1]-[3] and cannot be explained by Newtonian or non-Newtonian fluid theories because of its complexity and the large number of variables. The blood is modeled as a medium with six degrees of freedom which allows to change its motion position as forward/backward, up/down and left/right for translation in three perpendicular axes, combined with the changes in the orientation through rotation about three perpendicular axes [4]. The Fåhræus-Lindqvist effect or sigma effect explains the variation of the motion of the blood with the diameter of the vessel. This effect is done by a layer of plasma which does not contain the red blood cells and has an effective viscosity lower than of the whole blood because of the cell-free layer that reduces the flow resistance within the capillary making the effective viscosity less than of the whole blood [5]. The cell-free layer is thin (3 μm) and this property is insignificant to the capillaries with large diameters.

The plastic property of the material describes the hardening or the strain hard-

ening exponent in order to indicate the rate at which the material gains the strength during plastic deformation with higher values of strengthening. The curve σ-ε presents four stages with different deformation hardening (Figure 1) as:

(1) elastic region (Hooke law) for $\sigma_{pl} \approx 200$ MPa given by a straight line of slope E (Young's modulus ≈ 200 GPa). Above this point, the stress-strain relation stops to be linear, but elastic behavior persists;

(2) the stage of deformation with hardening coefficients of the largest stress that does not produce measurable permanent strain on unloading. In undergraduate practice, we have $\sigma_{pl} \approx \sigma_{el}$.

(3) the stage of deformation with hardening coefficients of the elastic limit $\sigma_{el} \approx$ 220 MPa;

and (4) a short stage of localization of the strain ending with fracture.

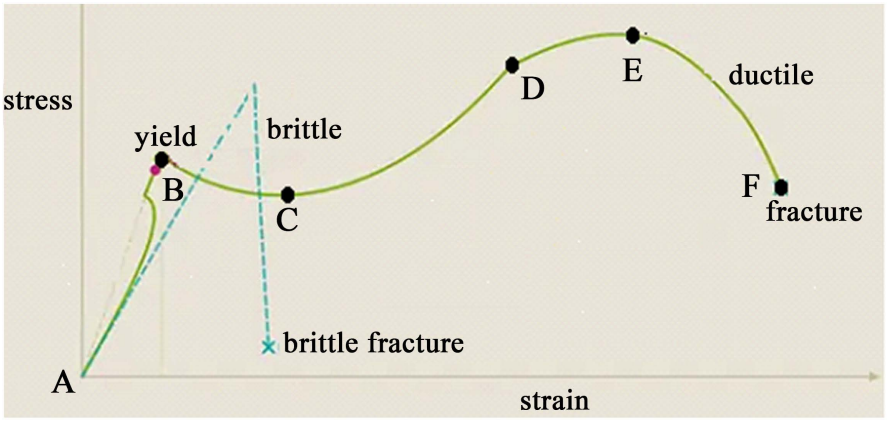


Figure 1. Ductile curve with a full elastic slope, upper/lower yield point, the strain hardening to ultimate tensile stress with necking initiated beyond this.

In Figure 1 the line AB is the elastic limit $\sigma_{el} \approx 220$ MPa, the line BC, the upper and lower yield $\sigma_y \approx 250$ MPa. The curve drops to a plateau and oscillates. The lines CD and DE describe the strain hardening for $\sigma \approx 400$ MPa and the line EF the necking and fracture.

The curve is headed to the fracture at $\varepsilon_f \approx 0.25$ - 0.35 with an elongation of aprox, 25% - 35%. The macromotion and the micromotion of the red blood cells are expressed as

$$x_k = \hat{x}_k(X,t),\ k = 1,2,3, \tag{1}$$

$$\xi_k = \chi_{kK}(X,t)\Sigma_k,\ K = 1,2,3, \tag{2}$$

where the capital Latin indices refer to the material coordinates X_k and the small indices to the spatial coordinates x_k.

2. The Fåhræus-Lindqvist Effect

Fahraeus and Lindquist effect (reported in 1931) explains the behavior of the blood flow in the large diameters tubes with average hematocrit of the capillary 29 - 221 μ less than for in the larger tubes The independent variables are the flow

rate, the feed reservoir hematocrit, the capillary diameter, the stirring rate in the reservoir and the content of the continuous phase of the protein. The dependent variables are the average hematocrit in the capillary tubes and the mixing-cup hematocrit of the blood flowing. For a steady flow of blood, the relative hematocrit is independent to the flow rate of the blood, to the protein content of the continuous phase of the red cell suspension and to the stirring rate in the reservoir [6]-[9].

The Fåhræus-Lindqvist effect is caused by the cell-free layer of plasma adjacent to the capillary walls with no red blood cells. So, its effective viscosity is lower than to the whole blood. The cell-free layer reduces the flow resistance in the vessels with a viscosity less than the viscosity of the whole blood [10]. The cell-free layer is very thin (approx. 3 μm) allowing that this effect to be insignificant in capillaries with larger diameters.

For the steady laminar of the blood flow in the small tubes with radius r_0, the ratio between the tube hematocrit H_t and the out flowing hematocrit H_0 is [11]

$$\frac{H_t}{H_0}=\frac{1}{2-\left(1-\frac{\delta}{r_0}\right)^2} \tag{3}$$

with δ the cell-free plasma layer thickness and r_0 the radius of the tube. The relationship between the tube hematocrit H_t and the discharge hematocrit H_d, D being the diameter of the tube [μm] is given by

$$\frac{H_t}{H_d}=H_d+\left(1-H_d\right)\left(1+1.7\exp\left(-0.415D\right)-0.6\exp\left(-0.011D\right)\right) \tag{4}$$

The formula (4) was developed by [12].

Several researchers tried to explain the Fåhræus-Lindqvist effect on the basis on the experimental data. So, the velocity profile of the core layer, the role of hematocrit in viscosity and the thickness of the cell-free layer appear as results of the property of the blood to be a two-phase fluid with one phase the core (cell) layer, suspended in plasma; and the other phase, the cell-free layer made from plasma. The plasma layer surrounds the suspended cell layer [13].

Also, the blood can be modeled as a single-phase body as

$$\eta_e=\eta_c\left[1-\frac{4\delta}{R}\left(\frac{\eta_c}{\eta_p}-1\right)\right], \tag{5}$$

where $\tau=\eta e$, with τ the stress, η the viscosity coefficient, and e the strain rate.

We present now a two-phase blood flow starting with the Upadhyay model [14]. For this, the uniform density ρ_m is written as

$$\frac{1+r_0}{\rho_m}=\frac{r_0}{\rho_c}+\frac{1}{\rho_p}. \tag{6}$$

The continuity equation for RBC phase, and for plasma phase respectively, are

$$\frac{\partial \rho_m}{\partial t} + \left(\rho_m v^l\right)_{,l} = 0 \tag{7}$$

where ρ_m is not a constant.

Here, Y is the volume of the blood which can be replaced by Ha/100, with Ha the volume percentage of the blood cells [15]. The volume covered by plasma is $(1 - Y)$. The equation (7) takes the forms

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial \left(Y\rho_c\right)}{\partial t} + \left(Y\rho_c v^l\right)_{,l} = 0 \tag{8}$$

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial \left(1-Y\right)\rho_p}{\partial t} + \left(\left(1-Y\right)\rho_p v^l\right)_{,l} = 0 \tag{9}$$

where v is the common velocity for both phases, ρ_c and ρ_p are densities of the core layer and the plasma layer, respectively.

The (8) and (9) are solved by using the cnoidal method [16]. The cnoidal method elaborates the solutions in terms of the Jacobi elliptic functions cn and sn. The solution is written as a sum between a linear superposition of cnoidal functions [17]

$$\theta_{lin} = 2\sum_{k=0}^{n} \alpha_k \mathrm{cn}^2\left[\eta; m_k\right], \tag{10}$$

and a nonlinear superposition of cnoidal functions

$$\theta_{nonlin} = \frac{\sum_{k=0}^{n} \beta_k \mathrm{cn}^2\left[\eta; m_k\right]}{1 + \sum_{k=0}^{n} \lambda_k \mathrm{cn}^2\left[\eta; m_k\right]} \tag{11}$$

with m_k parameters which take the values 0 or 1, and $\eta = kx - \omega t + \varphi$, with k the wave number, ω the frequencies and φ_j the phases.

3. Conclusion

The Fåhræus-Lindqvist effect describes the decreasing of the blood viscosity with decreasing of the vessel tube radius in vessels. The Fåhræus-Lindqvist effect has applications in the field of thin-film superelastic alloys, the shape memory alloys, MEMS and NiTi films. The Fåhræus-Lindqvist effect characterizes the lower viscosity in comparison with the viscosity of the whole blood. The apparent viscosity of the blood depends on the geometry of the instrument in which it is measured. The cell-free layer reduces the resistance of the blood to motion within the vessels making an effective viscosity less than of the whole blood. The cell-free layer is approximative 3 μm and then, this effect is insignificant in the capillaries with large diameters.

Author Contributions

Ligia Munteanu wrote the first draft of the manuscript. Ligia Munteanu and Veturia Chiroiu designed the study and analyzed the results. Rodica Ioan collected the data. All authors reviewed the manuscript and approved the final version.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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