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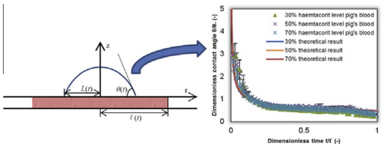
Spreading of blood drops over dry porous substrate: Complete wetting case

Tzu Chieh Chao, Omid Arjmandi-Tash, Diganta B. Das, Victor M. Starov *

Department of Chemical Engineering, Loughborough University, Loughborough LE11 3TU, UK

GRAPHICAL ABSTRACT



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ABSTRACT

Hypothesis: The process of dried blood spot sampling involves simultaneous spreading and penetration of blood into a porous filter paper with subsequent evaporation and drying. Spreading of small drops of blood, which is a non-Newtonian liquid, over a dry porous layer is investigated from both theoretical and experimental points of view.
Experiments and theory: A system of two differential equations is derived, which describes the time evolution of radii of both the drop base and the wetted region inside the porous medium. The system of equations does not include any fitting parameters. The predicted time evolutions of both radii are compared with experimental data published earlier.
Findings: For a given power law dependency of viscosity of blood with different hematocrit level, radii of both drop base and wetted region, and contact angle fell on three universal curves if appropriate scales are used with a plot of the dimensionless radii of the drop base and the wetted region inside the porous layer and dynamic contact angle on dimensionless time. The predicted theoretical relationships are three universal curves accounting satisfactorily for the experimental data.

1. Introduction

Dried blood spot (DBS) sampling is a method of blood collection, transportation and storage which has been investigated and used over the recent decades [1–6]. However, most studies of DBS have been focused on the clinical aspects, such as, developing new analytical method and improving their sensitivity of measurements, and the detection of new analytes. The mechanisms of blood spreading behavior during DBS sampling on DBS filter paper has not been investigated yet. The basic procedure of DBS sampling is to deposit a small but known amount of blood droplet on a filter paper where the droplet will spread, penetrate into and slowly dry out as a spotted sample. Hence, the sampling process can be described in terms of spreading of blood, which is a non-Newtonian fluid, over a thin porous substrate. In order to investigate the influence of the spreading/imbibition behavior on the DBS analysis, the development of a theoretical model is presented below.

The spreading of Newtonian liquids over smooth homogeneous surfaces has been investigated in [7–10]. It has been established that a singularity at the three phase contact line is removed by the action of surface forces [8,10]. The presence of roughness and/or a porous sublayer changes substantially the wettability of the substrate [11] and, hence, the spreading behavior [12–14]. The theoretical description of spreading over real surfaces is

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* Corresponding author. Fax: +44 (0)1509 223923.
E-mail addresses: T.Chao@lboro.ac.uk (T.C. Chao), O.Arjmandi-Tash@lboro.ac.uk (O. Arjmandi-Tash), d.b.das@lboro.ac.uk (D.B. Das), v.m.starov@lboro.ac.uk (V.M. Starov).

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Nomenclature

Latin

a	radius of pores (μm)
A	dimensionless parameter (–)
b, c, C	integration constant (–)
g	gravity acceleration value (m s^{-2})
h	height of the drop (mm)
K_n	permeability of the porous layer (mD)
k	flow consistency index (Pa s^n)
L	radius of the drop base (mm)
ℓ	radius of the circular edge of the wetted region inside the porous layer (mm)
m	porosity (–)
p	pressure (Pa)
r, z	co-ordinate system (mm)
t, T	time (s)
u, v	vertical and radial velocity components (m/s)
V	volume of the drop (μl)

Greek

γ	interfacial tension (dyn cm^{-1})
σ	surface tension (dyn cm^{-1})
$\dot{\gamma}$	shear rate (s^{-1})
Δ	thickness of the porous layer (μm)
δ	small parameter (–)
η	effective viscosity (mPa s)
θ	dynamic contact angle (°)
ν	dimensionless parameter (–)
ρ	density (kg m^{-3})
λ	effective lubrication parameter (–)
χ	dimensionless parameter (Eqs. (28) and (29)) (–)

Subscripts

0	initial value
p	porous layer
g	ambient air
c	capillary
η	viscous
Δ	complete saturation of the porous layer in the vertical direction
f	marks the constant value of the contact angle over the duration of the second stage
+	expansion
–	shrinkage
d	drop
m	corresponds to the moment when the drop base reaches its maximum value

Superscripts

$*$	characteristic value
–	dimensionless

usually based on an *ad hoc* empirical "slippage condition" [15–19]. In [20] the spreading of small drops of Newtonian liquids over thin porous layers saturated with the same liquid has been investigated. Instead of the "slippage conditions" Brinkman's equations have been used in [20] for the description of the liquid flow inside the porous substrate. In [21] the spreading of Newtonian liquid over dry porous substrates was investigated in the case of complete wetting.

Spreading of droplets of non-Newtonian liquids over smooth solid surfaces was considered in [22] in the case of complete wetting. Considerable deviations from the spreading of Newtonian liquids were found [22]. In [23] a simultaneous spreading and evaporation of droplets of Newtonian liquids were considered.

Below the liquid under investigation is spreading/imbibition of a blood drop, which is a non-Newtonian power-law liquid, over a filter paper. Hence, the problem under investigation is similar to that considered in [21] when a drop of Newtonian liquid spreads over a dry porous layer, however, the difference is that now the liquid is a non-Newtonian blood. The experimental result on blood drops spreading over Whatman 903 filter paper (GE healthcare, UK) has been presented in [24]. The experimental results presented in [24] show that the blood spreading deviates from the corresponding Newtonian liquid [21] in two ways: (i) the droplets spreading governs by a different law as compared with [21] and (ii) non-Newtonian liquid imbibition into a porous substrate differs from that of Newtonian liquids.

The problem is treated below under the lubrication theory approximation and in the case of complete wetting. Spreading of "big drops", that is, bigger as compared with thickness of the porous substrate but still small enough to neglect the gravity action over "thin porous layers" is considered below.

2. Theory

The kinetics of blood motion in the drop both above and within the porous layer itself is taken into account below. It is assumed that the thickness of the porous layer, Δ, is much smaller than the drop height, that is, $\Delta \ll h^*$, where h^* is the scale of the drop height. The drop profile is assumed to have a low slope, $h^*/L^* \ll 1$, where L^* is the scale of the drop base, and the influence of the gravity is neglected (small drops, Bond number $\rho g L^{*^2}/\gamma \ll 1$, where ρ, g, and γ are the liquid density, gravity acceleration and the liquid–air interfacial tension, respectively). That is, only capillary forces are taken into account.

Under such assumptions a system of two differential equations is deduced below, which describes the time evolution of the radii of both the drop base, $L(t)$, and the wetted region inside the porous layer, $\ell(t)$, (Fig. 1).

2.1. Droplet profile

According to [22] in the case of the capillary spreading the droplet profile in the central part of the droplet, except for a small vicinity of the three phase contact line, can be presented as a spherical cap even in the case of non-Newtonian liquids, which is similar to the case of Newtonian liquid [21]:

$$h(t,r) = \frac{2V}{\pi L^4}(L^2 - r^2), \quad r < L(t) \tag{1}$$

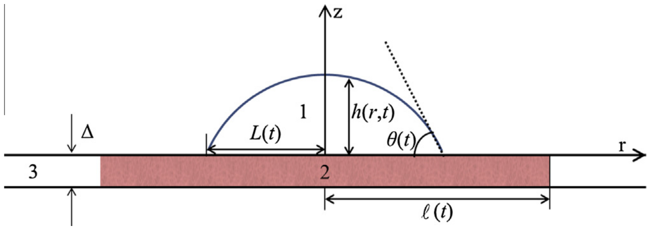

Fig. 1. Cross-section of the axis-symmetric spreading drop over initially dry filter paper with thickness Δ. 1 – liquid drop; 2 – wetted region inside the porous substrate; 3 – dry region inside the porous substrate. $L(t)$ – radius of the drop base; $\ell(t)$ – radius of the wetted area inside the porous substrate; Δ – thickness of porous substrate; $\theta(t)$ – contact angle; r, z co-ordinate system.