Radial Capillary Transport from an Infinite Reservoir

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Abstract Radial capillary transport occurs, for example, when wine spreads in the tablecloth, ink in paper, rain drops in textiles, or dye into yarn. It is of technical relevance for propellant and other liquid transport in space. We present a theoretical and experimental study on the more basic situation when liquid spreads radially from an infinite reservoir. Our theoretical model predicts both outward and inward radial transport in a porous screen. While the outward wicking is fed by a circular wick in the center, the inward wicking is fed by a ring-like wick from the outside. For both cases, an analytical solution is obtained in terms of time versus radius as well as radius versus time aided by the Lambert W function. In the experiments, we use four different filter papers combined with three cylindrical wicks for outward wicking and one ring wick for inward wicking, respectively. The wicking process is recorded by a digital camera. Afterward, the resulting image series are evaluated with Matlab routines to detect the wicking front line. From the wetted area, we derive the mean radius versus time. Beside radially outward and inward wicking, we consider also experimental reference data from horizontal and vertical wicking in a strip.

Keywords Wicking · Radial capillary transport · Porous medium · Lucas–Washburn · Imbibition

Nomenclature
\( \phi \) Porosity of the screen
\( \mu \) Dynamic viscosity (kg/ms)
\( \pi_1 \) Dimensionless parameter
\( \pi_2 \) Dimensionless parameter
\( \pi_3 \) Dimensionless parameter
\( \rho \) Density of liquid (kg/m\(^3\))
\( \rho_h \) Regression coefficient (horizontal strip exp.)
ρ_v Regression coefficient (vertical strip exp.)
σ Surface tension (N/m)
θ Contact angle
a Viscous wicking constant (m²/s)
a_h a found in horizontal strip experiment (m²/s)
a_v a found in vertical strip experiment (m²/s)
\bar{a} Mean value of a (m²/s)
\Delta a Error of a (m²/s)
b Inertial wicking constant (m²/s²)
Ca Capillary number
\Delta h Height difference between screen and reservoir (m)
H Height (=thickness) of the screen (m)
K Permeability of the screen (m²)
L Characteristic length (m)
Oh Ohnesorge number
r Radial coordinate (m)
r_0 Initial radius of the wetted spot (wick radius) (m)
R Radius of the wetted spot (m)
R_k Mean static pore radius (m)
R* Dimensionless spot radius
s Distance between screen and camera (m)
t Time (s)
t* Dimensionless time
v Velocity of the front line (m/s)
V Liquid flow rate (m³/s)
V* Dimensionless liquid flow rate
w Strip width in horizontal reference experiment (m)
W( ) Lambert W function
x_0 Initial meniscus position in the strip experiments (m)
X Meniscus position in the strip experiments (m)

1 Introduction

Capillary transport is a basic mechanism that works under variable gravity conditions including weightlessness. Therefore, it is also of interest for space applications such as propellant management devices that ensure an undisturbed fuel supply. Within these devices, the capillary force is bound to porous, mostly woven structures such as stainless steel weaves. If the liquid fuel comes in point contact with the porous structure for the first time, then it imbibes it radially outward. If due to evaporation a part of the porous structure has fallen dry, then it will be re-wetted by radially inward imbibition.

Linear capillary transport in a porous medium is often modeled by the capillary bundle theory. Here, one assumes that the pores are interconnected, homogeneously distributed, and thus act like a bundle of identical capillary tubes with an effective tube radius. Therefore, one can rely on the basic works of Lucas (1918) and Washburn (1921a, b) on single capillaries. Consequently, when it comes to radial capillary transport in a porous medium, one might assume a radial capillary as done by Marmur (1988). He analytically studies the radially outward movement of a meniscus between two parallel plates with a liquid supply hole in the middle. This theory is experimentally supported by Danino and Marmur (1994) who use filter