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Rheometric assessment and numerical simulation of steady-state and periodic flows of fabric-water mixtures in household top-load washing machines

Felipe R. Loyola[a,*], *Waldyr de Lima e Silva Jr.*[a], *Luiz G.C. Campos*[b], *Christian J.L. Hermes*[c,*]

[a] *Department of Mechanical Engineering, Federal University of Paraná, 81531990 Curitiba, PR, Brazil*
[b] *Advanced Product Development Fabric Care, Electrolux Major Appliances Latin America, 81520900 Curitiba, PR, Brazil*
[c] *POLO Research Laboratories, Department of Mechanical Engineering, Federal University of Santa Catarina, 88040970 Florianópolis, SC, Brazil*

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ABSTRACT

The washing process in household top load washing machines relies on the mass and momentum transport from an agitator to the fluid stream. In such cases, such a periodic flow follows a pattern that recalls the so-called Taylor–Couette flow, whose main characteristic is the confinement between two rotating cylinders. The present paper is aimed at steady-state and periodic-unsteady-state flows of non-Newtonian fluids formed by fabric and water mixtures. A simplified coaxial double cylinder geometry is used as the physical domain for the numerical analyses, whereas an agitation profile (angular swept and speed) was imposed to the inner cylinder. The rheological properties of the working fluid made of aqueous fabric suspensions were obtained in-house by solving the Couette inverse problem using a wide-gap rheometry approach. Four different NNF models have been evaluated – namely, Bingham, Casson, Robertson–Stiff, and Herschel–Bulkley – for data reduction and correlation, when it was observed that the last one provided the best results for different fabric-water suspensions. Numerical simulations were performed using a 3D homemade finite-volume model, and experimental tests (234 runs at steady-state and 80 runs at periodic flow conditions) were carried out by means of a purpose-built testing facility. The simulation model was validated against experimental data indicating an agreement between numerical and experimental torques and velocities within the 20% thresholds.

1. Introduction

A washing machine is a household appliance whose main purpose is to remove dirt from a given amount of fabric by means of mechanical, thermal and chemical processes taking place simultaneously during the washing cycle (Van den Brekel, 1987). Such a home appliance may be mounted with either horizontal or vertical axis, where the former is more likely found in European countries, and the latter in Australasia and the Americas, including Brazil (Bansal et al., 2011).

A top-load, vertical axis washing machine is comprised of a structure that supports a water reservoir (outer bowl) concentric to a perforated drum (spin bowl) that rotates without angular restrictions. Such an assembly is made also concentric to an agitator, which is responsible for moving the mixture formed by fabric, water and detergent. The agitator is connected to an electric motor by a transmission so that the torque and the angular velocity can be both controlled. The outer bowl is filled with water through a hydraulic system comprising a pump, a suction valve, and a water level sensor. In general, the wash-

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* *Corresponding author.*
E-mail addresses: loyola@ufpr.br, hermes@polo.ufsc.br (C.J.L. Hermes).

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Nomenclature

Roman

h	Air-water interface height, [m]
H	Cylinder height, [m]
k	Radius ratio, [–]
K	Exponential growth of the stress, [–]
m	Flow consistency index, [Pa s^n]
n	Flow behavior index, [–]
P	Pressure, [Pa]
r	Radial position, [m]
R	Cylinder radius, [m]
Re	Reynolds number, [–]
t	Time, [s]
T	Torque, [N m]
Ta	Taylor number, [–]
v	Velocity, [m s^{-1}]
z	Axial position, [m]

Greek

$\dot{\underline{\underline{\gamma}}}$	Rate of strain tensor, [s^{-1}]
$\dot{\gamma}$	Shear rate, [s^{-1}]
$\dot{\gamma}_0$	Shear rate correction factor, [s^{-1}]
δ	Radius gap, [m]
η	Rheological viscosity (apparent viscosity), [Pa s]
θ	Angular position, [–]
μ	Dynamic viscosity, [Pa s]
ρ	Density, [kg m^{-3}]
$\underline{\underline{\tau}}$	Shear stress tensor, [Pa]
τ	Shear stress tensor magnitude, [Pa]
τ_0	Yield stress, [Pa]
ω	Angular velocity, [rad s^{-1}]
Γ	Cylinder aspect ratio, [–]
Δt	Time step, [s]

Subscripts

inn	Inner cylinder
out	Outer cylinder
r	Radial component
z	Axial component
θ	Tangential component

Abbreviations

NNF	non-Newtonian fluid
SSE	Sum of square errors
RMS	Root mean square

ing process depends on a wide set of parameters, such as the spin bowl and agitator geometries, the agitation profile (i.e., temporal variation of torque, angular swept and speed), the water level, and the temperature of the mixture formed by water, fabric, detergent, among other additives (Campos and Hermes, 2016).

It is worth mentioning that the efficiency of the mechanical washing relies on the mass and momentum transport from the agitator to the fluid stream, thus resulting in a periodic circular flow (Loyola, 2017). Because of the complexity of the flow, most of the information about the washing process – which is still scarce in the open literature – is of empirical or semi-empirical nature (Van den Brekel, 1987; Campos and Hermes, 2016; Janáčová et al., 2001). Nonetheless, a satisfactory level of understanding of the mechanical process can be obtained from the so-called Taylor–Couette flow, whose main characteristic is the confinement of a viscous fluid between two rotating cylinders (Donnelly, 1991).

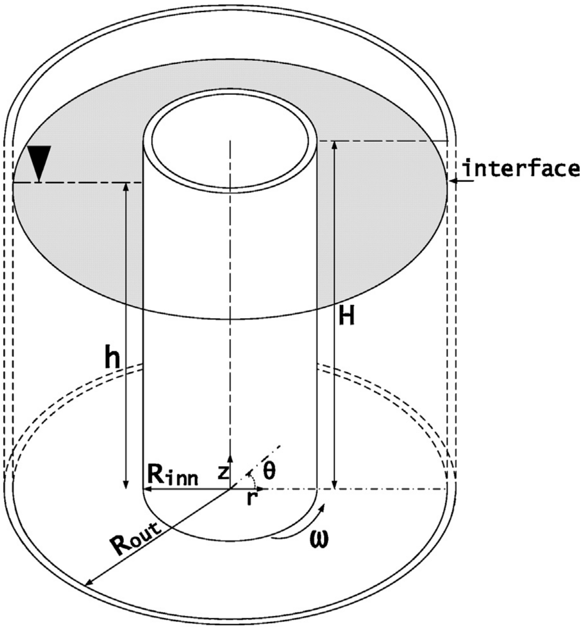

Fig. 1 – Schematic representation of the physical domain.

The physical model for a typical Taylor–Couette flow is depicted in Fig. 1. The fluid column height is denoted by h, whereas the cylinders total height is denoted by H. For the sake of simplicity, the outer cylinder (drum) is held stationary while the inner one (agitator) rotates independently with an imposed angular velocity ω_{inn}. The radius gap ($\delta = R_{out} - R_{inn}$), radius ratio ($k = R_{inn}/R_{out}$) and aspect ratio ($\Gamma = h/\delta$) are the geometric parameters. The dimensionless flow parameters are the rotational Reynolds number (Re) and Taylor number (Ta), the former is the ratio between inertial and viscous forces acting in the flow, whereas the latter relates the same forces taking the cylindrical geometry into account, yielding

$$\mathrm{Re} = \frac{\rho\,(\omega R_{inn})\,\delta}{\mu} \tag{1}$$

$$\mathrm{Ta} = \left(\frac{\rho\omega}{\mu}\right)^2 R_{inn}\delta^3 = \left(\frac{1}{k} - 1\right)\mathrm{Re}^2 \tag{2}$$

In order to represent the behavior of a washing machine, the (bottom) base can also rotate with the inner cylinder, thus enhancing the power transmission to the fluid stream.

If one looks for literature on mechanical washing, just a few works will come out. For instance, Eger (2010) analyzed by means of a commercial CFD package the flow mixing in alternated motion focusing on flows of pure water in vertical drum washing machines in which the drum (outer bowl) is rotated by the motor. An experimental rig was built on purpose so that the velocity field was measured to validate the model. The water level, rotational velocity, and geometry parameters were analyzed and showed a satisfactory level of agreement with the numerical counterpart. Aiming at advancing the knowledge about the mechanical aspects of the washing process. Akcabay et al. (2014) put forward two and three-dimensional models to solve the flows of fabric-water suspensions by means of the Peskin's immersed boundary method. Calvimontes (2009) performed a topographic characterization of polyester and cotton fabric to understand the influence of the morphology of yarns and fibers aiming at the effects of the washing cycles on topography, spreading, wetting and dirt accumulation.

One can see that there is a lack of studies concerning the Taylor–Couette flows with fabric-water suspensions as working fluids. Moreover, from the authors' best knowledge, there are no models available in the open literature for fabric-water suspensions. Therefore, to simulate the flow of fabric-water suspensions in a Taylor–Couette geometry, a numerical methodology based on CFD techniques for steady-state and periodic fluid flows was developed. Experimental tests were carried out in a purpose-built experimental facility not only to