



# On the insertion of a thin gas layer in micro cylindrical Couette flows involving power-law liquids



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## ABSTRACT

Consideration is given to the fluid flow and heat transfer repercussions for introducing a thin (micro) gas layer into a cylindrical Couette flow assembly dealing with a power law liquid (lubricant). The trio influence of the thin gas layer on (1) the torque required for activating the lubrication process, (2) on the maximum temperature of the shaft (inner cylinder) and (3) on Nusselt number of the two-phase flow configuration are studied analytically. The results demonstrate that the thin gas layer normally contributes to reduce in the torque to set the fluid in motion and to downscale the maximum temperature at the shaft, especially for the sub-category of shear thickening liquids. However, in the sub-category of shear thinning liquids, the above-mentioned positive roles attributed to the micro gas layer hold true only for a limited number of flow configurations depending on several factors such as the Knudsen number, the accommodation coefficients and the rheological parameters of the liquid. It is further corroborated that the thin gas layer stabilizes or destabilizes the flow, depending on the magnitude of the power index number characterizing the liquid.

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## 1. Introduction

Nowadays, fluid flow and heat transfer analyses in micro-electro-mechanical systems (MEMS) have received paramount interest for the advancement of on-a-chip micro fabrication technology. It is well-known that the no-slip boundary condition in the velocity fields near the wall breaks down. Under these circumstances, the onset of 'slippage' is determined by the well-known Knudsen number,  $Kn$ , defined as  $Kn = \lambda/L_c$ . Here,  $\lambda$  is the mean free path and  $L_c$  is the characteristic length of the configuration under study. The prevalent criterion  $0.001 < Kn < 0.1$  limits the analysis to continuum and gaseous slip flow [1,2]. Fundamentally, the development of a depleted liquid region over a hydrophilic surface may form a gas layer and therefore leads to slippage [3–10]. This situation may even occur when the surface is nearly smooth [10,11]. Although the slippage phenomena has been demonstrated experimentally by several scholars [3,6,12–16], the mechanism for the velocity/temperature slip due to the gas pockets residing along the system boundaries or the formation of Nano bubbles at the solid–liquid interface is not well understood.

Owing to the fabrication process of micro technologies (micro-motors, -pumps, -turbines and micro-bearings, -electrical ma-

chines, -swirl nozzles, commercial rheometers) analysis of the transport phenomena associated with fluids flowing in rotating/planar micro configurations have been widely investigated. Representative publications cover gases [17,18] and electro-rheological liquids [19]. Their studies focused on the hydrodynamic attributes of micro flow patterns [20–27], or concentrated on the thermal aspects [28–30]. There are also some works addressing the second law analysis of such flows [30,31]. For example, Maureau et al. [20] analyzed micro bearings represented as an eccentric cylinder rotating inside a stationary housing. These authors demonstrated that the force and torque on the load-bearing inner cylinder increase with increments in eccentricity and decrease with increments in the slip. Watanabe et al. [21] reported the shear reduction over a single phase water repellent grooved macro channel formed by two concentric cylinders. The slip flow effect is considered by Le et al. [22] in order to estimate load-carrying capacity and dynamic coefficients of micro gas-lubricated journal bearings. Employing a Lattice Boltzmann method (LBM), Chen and Tian [30] studied the characteristics of entropy generation due to heat transfer and friction in the transient state, as well as in the steady state for thermal micro-Couette flow under the framework of the slip-flow regime.

Although extensive research on the related problem of micro planar/cylindrical Couette flow has been conducted, a detailed literature review reveals that the two-phase (liquid–gas) micro cylindrical Couette flow has been rarely investigated. Recently, Jiji and

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### Nomenclature

$E$	function of coordinates (dimensionless), Eq. (3)	$\mu_{0,1}$	consistency constant
$h$	velocity/temperature slip coefficient, Eq. (9)	$\rho$	density
$K$	stability parameter, Eq. (13)	$\tau$	shear stress
$k$	Thermal conductivity	$\sigma$	momentum accommodation coefficient
$Kn$	Knudsen number, Eq. (10)	$\lambda$	mean free path
$Nu$	Nusselt number	<i>Subscripts/superscripts</i>	
$n$	behavior index	$c$	characteristic
$r$	radial coordinate, (dimensionless)	$g$	gas
$R$	radius	$l$	power law liquid
$T$	Temperature (dimensionless), Eq. (1)	$g-l$	interface between the gas and liquid layers
$u$	velocity, (dimensionless), Eq. (1)	$u$	velocity
$V$	velocity	$T$	temperature
<i>Greek symbols</i>		$*$	dimensional variables, Eq. (1)
$\Omega$	angular velocity	$\sim$	relative variables, Eqs. (1), (20), (21), and (23)
$\mu$	viscosity		

Danesh-Yazdi [32], Shamshiri et al. [31,33] addressed the case dealing with two immiscible fluids (a gas and a liquid), filling a narrow gap between a shaft and its concentric micro cylindrical housing. For the first time, Jiji and Danesh-Yazdi [32] found that the torque required to rotate the liquid in the annular space is significantly reduced by introducing a thin gas layer adjacent to the shaft. Also, these authors reported that the reduction in shaft temperature is enhanced through a combination of high energy accommodation coefficient and low momentum accommodation coefficient. Later, Shamshiri et al. [31,33] concluded that introducing a gas layer into the micro domain always contributes to the attenuation in the shear stress at the shaft and consequently, reducing the torque required to activate the system, which constitutes a desirable factor. However, it was demonstrated that; depending on the thermal case considered, this may be accompanied by some drawbacks, such as high temperatures at the shaft surface or worse functionality of the system with respect to the second law of thermodynamics. In Ref. [32], the stability nature of the two-phase problem was treated in a simplistic way that was similar the single phase flow criteria for stability declared by Taylor [34]. Therefore, the impact for introducing a thin gas layer (micro gas layer) on the flow stability has not been investigated so far. Historically speaking, the hydrodynamic stability of fluid flowing between the two rotating cylinders has been a model system to understand many aspects of fluids dynamics. It is well-known that such a flow is always stable when the outer cylinder rotates and the inner cylinder is at rest [34]. However, in the reverse case (stationary outer cylinder and rotating inner cylinder), the onset of instability (when the angular velocity of the inner cylinder exceeds a pre-set value) must be taken into account. This singular phenomenon has been addressed in more than 2000 papers in the archival literature since the pioneering work of Taylor [34] was published. Particular attention has been paid to several parameters, such as elasticity [48], high co-rotation [49], confinement [50], obstruction [51], shear thinning or yield stress [37,52] and their influence on the onset of instability. Another assumption made in Refs. [31–33] is that the liquid was idealized as Newtonian. Because the shear thinning/thickening or yield stress properties are of keen interest from an industrial point of view, such materials are now used widespread in a large number of applications as cited in Refs. [35–37] (oil drilling, cosmetics, building materials, foods, paints). Besides, many synthesis lubricants contain high molecular weight polymers, which impart strong non-Newtonian behavior [35] and may be generalized by the power law (see e.g. [38–44]). Consequently, understanding the hydrodynamic aspects in a

two-phase gas–liquid micro-cylindrical flow is imminent. Specially, analytical investigations are always of more interests. For example, Ferras et al. [36] presented analytical solutions for both Newtonian and inelastic non-Newtonian fluids with slip boundary conditions in both Couette and Poiseuille flows using the Navier-based linear and non-linear slip laws.

In this paper, an analytical study is carried out to elucidate the implications of introducing a thin gas layer on the hydrodynamic aspects of the two-phase gas viewed as power law liquid. One objective centers in the hydrodynamic attributes of the thin gas layer in changing the shear stress at the shaft and consequently, diminishing the torque required to activate the system. Another objective pertains to the changes that the gas layer imposes on the stability of the two-phase flow.

In synthesis there are three bullet points that describe the essence of the present research,

- It is shown that the analytical treatment can be made for generalized liquids (obeying the power law) as well as the regular Newtonian case ( $n = 1$ ).
- The use of the micro gas layer for curtailing the torque required for lubrication and abating the maximum temperature at the shaft is recommended in Refs. [31–33] for regular (Newtonian) liquids. In this paper, by considering all types of lubricants generalized by power law, it is shown that the use of the micro gas layer must be avoided in some flow configurations. For example, when the behavior index of the liquid,  $n$ , is lower than 0.6, an elevation in the torque required for lubrication (up to 6%) and an increment in the maximum temperature at the shaft (up to 40%) are reported depending on Knudsen number, accommodation coefficients and the rheological parameters of the liquid.
- In this paper, using an energy gradient based stability analysis (see Dou [45–47]), it is shown that the use of the micro gas layer must be avoided in some flow configurations for lubricants with generalized power law fluids.

## 2. Physical system

### 2.1. Base flow

Sketched in Fig. 1 are two fluids: a gas and a power law liquid, filling the narrow gap between a shaft (inner cylinder) of radius  $R_g$  and a concentric micro cylindrical housing of radius  $R_l$ . The shaft rotates at the angular velocity  $\Omega_g$  and is thermally insulated. The

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