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Effects of rarefaction, viscous dissipation and rotation mode on the first and second law analyses of rarefied gaseous slip flows confined between a rotating shaft and its concentric housing

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ABSTRACT

A parametric analytical study is carried out to scrutinize the mechanism of fluid flow, heat transfer and entropy generation in a low-speed rarefied gaseous flow confined between a shaft and its concentric housing, i.e., the cylindrical Couette flow. In the first law analysis, closed form solutions for the radial temperature profiles are obtained by incorporating the calculated velocity distribution into the energy equation. The derivations for three thermal cases, which are founded on imposing different thermal conditions, namely, the Uniform Heat Flux (UHF) and the Constant Wall Temperature (CWT) boundary conditions, are presented. In the second law analysis, the contributions of thermal diffusion and fluid friction irreversibility to the total entropy generation in the micro domain are illustrated, and the relevant expressions for the Bejan number and the entropy generation number as well as the average entropy generation rate are derived. Finally, the variations of major variables with influential parameters such as the Knudsen number, the Brinkman number and rotation mode are investigated to elucidate the associated effects of rarefaction phenomenon, viscous dissipation and geometric condition on the characteristics of the flow.

1. Introduction

Due to its indispensability of application in different practical areas, the branch of the so-called micro-electro-mechanical systems (MEMS) is going to be considered as an inseparable part of any scientific and industrial field. The issue of miniaturization corresponds to increased chemical yields, lower reagent consumption, enhanced sensitivity, reduced processing time and more importantly, enhanced functionality, which cannot be achieved in conventional macro devices. Because of the larger surface to volume ratio of the micro-fluidic systems, irreversibility associated with the presence of influential phenomena such as superficial friction, viscous dissipation and characteristics of convective heat transfer may have significant influence on the total efficiency of the media [1–5].

The entropy generation minimization concept, developed by Bejan [1,2], which is based on the second law of thermodynamics has received particular attention with the increasing awareness of the limits of world energy resources. The reason must be sought in the fact that entropy generation destroys the available work of a system and as a result, imposes considerable extra costs to any manufacturing unit [6,7].

According to the above, a special understanding of the fundamental physics associated with flow and heat transfer process and also entropy generation (exergy destruction) concept in miniaturized devices —which is considerably different from that of their macroscale counterparts— seems to be absolutely necessary. Achieving such a perception plays a very important role not only in improving the design and performance of MEMS (as energy-producing, -converting and -consuming systems) but also in a better utilization of existing resources.

The main attributes of the micro-scale flows can be characterized through a nondimensional number called Knudsen number, Kn, which is defined as the ratio of the mean free path of the molecules to the characteristic length of the system. The case of $Kn < 0.01$ is referred to as the continuum regime, in which the conventional hydrodynamic equations, i.e., the Navier-Stokes equations with no velocity slip boundary conditions and the Fourier heat conduction equation with no temperature jump boundary condition, are the appropriate governing equations. The values of $0.01 \leq Kn < 0.1$ are related to the slip flow regime in which

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the already mentioned boundary conditions seem to fail and velocity slip and temperature jump will appear on the solid boundaries and the Navier-Stokes-Fourier (NSF) equations should be solved subject to the slip/jump boundary conditions. As the Knudsen number approaches higher values, after a transition period, the free molecular flow regime is experienced [3,4].

Numerous studies have been carried out to scrutinize transport characteristics of flow in micro systems. Regards may refer to the available excellent research papers in the literature (e.g. [8–22].). However, the issue of entropy generation in micro-scales has not been addressed well and in this respect, only a few papers are available in the open literature. In other words, despite the first law analysis of micro-thermo-fluidic systems, the second law analysis has not received much respect and is still an open problem.

Most of the already mentioned studies have concentrated on numerical investigation of second law analysis in micro-scales [23–37]. However, the current study is analytical-approach oriented and tends to find simplified models for micro-thermo-fluidic structures based on the NSF equations, which can find extended utilization in engineering applications and other practical areas. Hence, in the following, we review some of the previous analytical investigations describing entropy generation phenomenon in some typical micro geometries such as straight micro channels/Couettes, micro tubes and micro annuli. Hooman [38] presented closed form solutions for fully developed temperature distribution and entropy generation due to forced convection within microducts and micropipes in the slip flow regime. Avci and Aydin [39] applied the entropy analysis to two different micro geometries: microtube and microduct. Hydrodynamically and thermally fully developed slip flow with constant properties is examined using the previously obtained velocity and temperature profiles. A parametric study is carried out to determine the combined effects of the Brinkman and Knudsen numbers on the entropy generation. Employing a porous medium approach, Abbassi [40] performed an analytical solution to discuss the first and second law analyses for flow in a uniformly heated microchannel heat sink. Within this study, average entropy generation rate is utilized as a criterion for assessing the system performance. Finally, the effect of influential parameters such as, channel aspect ratio, group parameter, thermal conductivity ratio and porosity on thermal and total entropy generation is investigated. Arikoglu et al. [41,42] studied the effect of slip on entropy generation in Magneto-Hydro-Dynamic (MHD) flow over a rotating micro disk using a semi-numerical analytical solution technique. The nonlinear governing equations of flow and thermal fields are reduced to ordinary differential equations by the Von Karman approach, and then solved via differential transform method (DTM). Yari [43] presented the first and second laws of thermodynamics analysis for laminar forced convective heat transfer of a Newtonian fluid in a microchannel between parallel plates. Through this study, hydrodynamically and thermally fully developed flow with constant properties is examined. Two different forms of the thermal boundary conditions are considered. The velocity and temperature profiles are analytically determined as functions of the Brinkman and Knudsen numbers. The influence of viscous dissipation on entropy generation in fully developed forced convection single-phase Newtonian and non-Newtonian liquid flow in a circular microchannel under imposed uniform wall heat flux is studied by Hung [44,45]. In the first law analysis, closed form solutions of the radial temperature profiles for the models with and without viscous dissipation term in the energy equation are obtained. In the second law analysis, for different Brinkman number and dimensionless heat flux (or power-law index), the variations of dimensionless entropy generation and Bejan number as functions of the radial distance are investigated. Yari [46] investigated the entropy generation in a microannulus flow. Fully developed laminar flow is considered with uniform heat flux at the walls. Viscous dissipation effect, velocity slip and temperature jump at the wall are taken into consideration. The effects of the Knudsen and Brinkman numbers on velocity, temperature profiles, entropy generation rate and average entropy generation are discussed. Ibáñez and Cuevas [47] considered a Lorentz-force driven flow in a parallel plate microchannel created by a transverse magnetic field and an injected electric current, assuming a thermally fully developed flow and conducting walls of finite thickness. Velocity, temperature and current density fields in the fluid and walls are used to calculate the global entropy generation rate. Conditions under which this quantity is minimized are also determined for specific values of the geometrical and physical parameters of the system.

The current survey is triggered by the absence of simple analytical investigations of the first and second law analysis for low-speed rarefied flow between rotating micro-structures, which can find extended applications in the design and fabrication process of many practical micro technologies such as micro-motors, -pumps, -turbines and micro bearings and also rotating electrical machines, swirl nozzles, rotating disks, standard commercial rheometers and other chemical and mechanical mixing equipment (see Maron and Cohen [48]). Hence, in the following we aim at presenting closed form solutions of the momentum and energy fields and we are also concerned with understanding the nature of the entropy generation concept of cylindrical Couette flow in the slip flow regime.

2. First law analysis

2.1. Mathematical formulation

Consider a shaft of radius r_i and angular velocity ω_i concentrically positioned inside its hosting of radius r_o and angular velocity ω_o (Fig. 1). The gap is filled with a rarefied gas while the system boundaries are under the influence of either Constant Wall Temperature (CWT) or Uniform Heat Flux (UHF) conditions. For the

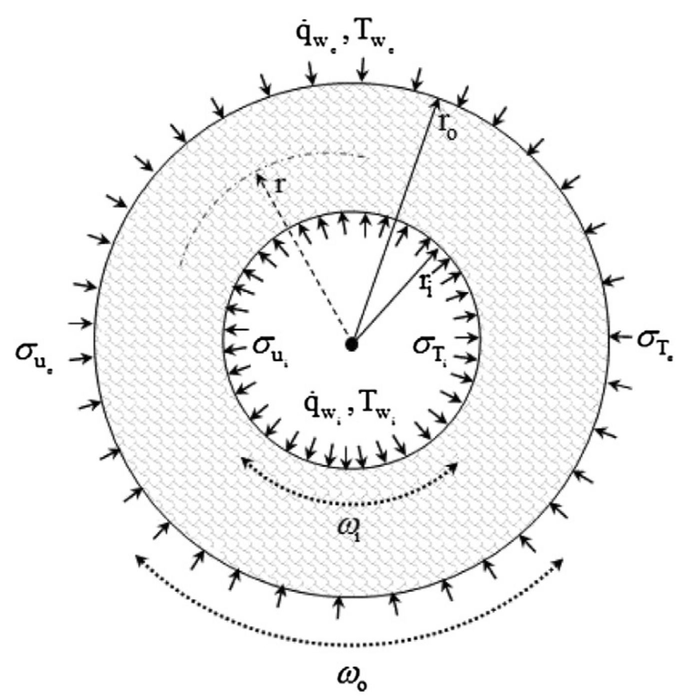

Fig. 1. Schematic diagram of the configuration and imposed boundary conditions.