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Second law analysis of an infinitely segmented magnetohydrodynamic generator

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ABSTRACT

The performance of an infinitely segmented magnetohydrodynamic generator is analyzed using the second law of thermodynamics entropy generation criterion. The exact analytical solution of the velocity and temperature fields are provided by applying the modified Hartmann flow model, taking into account the occurrence of the Hall effect in the considered generator. Contributions of heat transfer, fluid friction, and ohmic dissipation to the destruction of useful available work are found, and the nature of irreversibilities in the considered generator is determined. In addition, the electrical isotropic efficiency scheme is used to evaluate the generator performance. Finally, the implication of the Hall parameter, Hartmann number, and load factor for the entropy generation and the generator performance are studied and the optimal operating conditions are determined. The results show that the heat transfer has the smallest contribution to the entropy generation compared to that of the friction and ohmic dissipation. The application of the Hall effect on the system showed an appreciable augmentation of entropy generation rate which is along with what the logic implies. A parametric study is conducted and its results provide the generated entropy and also efficiency diagrams which show the influence of the Hall effect on the considered generator.

1. Introduction

The second law of thermodynamics has found extensive applications in the optimization of a vast variety of systems and devices in recent years [1]. One of the main applications of this law among researchers in the field is that of analyzing power cycles and power generating devices. Nonetheless, magneto hydrodynamic (MHD) power generators have not really received respectable considerations yet. The general framework of treating MHD devices through the second law analysis was devised by Salas et al. [2]. The nature of intrinsic irreversibilities in MHD devices was explored in the above work and, as an example, to clarify the different stages of the method; the Hartmann model was chosen and analyzed. Later on, the approach was used to optimize the oscillatory Hartmann flow by Ibanez et al. [3]. The same authors considered the radial creeping MHD flow between parallel circular disks from the same viewpoint [4]. The other notable work in this respect was the second law analysis of free convection in a porous enclosure exposed to an external magnetic field by Mahmud and Fraser [5]. Makinde et al. [6] studied the entropy generation and irreversibility through applying the perturbation method. Guria et al. [7] investigated the Hall effect in porous disk and solved the related equations by the Laplace Transform method. Several numerical methods have been applied to solve the flow equation in MHD generators to reach the velocity and temperature profiles and other main parameters, such as, entropy generation based on the Hartmann number and other MHD key parameters. Zeeshan et al. [8] numerically investigated the effect of magnetic dipole on viscous ferro-fluid past a stretching surface with thermal radiation. They illustrated the effect of a number of key parameters such as ferromagnetic parameter, the Prandtl number and thermal radiation on temperature profile, velocity profile, skin friction, the Nusselt number, and pressure. Ellahi and Hameed [9] presented a numerical method to study the effects of magnetohydrodynamics, heat transfer and nonlinear slip on the walls of a channel for steady non-Newotonian flows. They used the Chebyshev spectrsl collection method to solve the appropriate non-linear differential equations. Rabhi et al. [10] numerically investigated the irreversibility within a porous micro duct subjected to an external oriented magnetic field. They used the Modified Lattice Boltzmann Method to investigate the effects of the magnetic field and other parameters on the entropy generation. A mathematical analysis was conducted by Rashidi et al. [11] on two dimebssional fluid flows to study a stream wise transverse magnetic fluid flow with heat transfer around an obstacle embedded in a porous medium. They used the Darcy-Brinkman-Forchheimer model along with the Maxwell equa-

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Nomenclature

B_0	magnitude of the uniform external magnetic field, Tesla
E	electric field vector, V/m
E_x	axial component of electric field, V/m
E_y	transverse component of the electric field, V/m
E_x^*	nondimensional component of electrical field, $E_x/B_0\bar{u}$
e	Internal energy
H	half of the separation distance between the walls normal to the magnetic field, m
Ha	Hartmann number, $(\tilde{\sigma}B_0^2H^2)^{1/2}/\mu$
j	electrical current vector, A
j_x	axial component of the electrical current vector, A
j_y	transverse component of the electrical current vector, A
J_x	nondimensional axial component of the electrical current, $j_x/\tilde{\sigma}B_0\bar{u}$
J_y	nondimensional transverse component of the electrical current, $j_y/\tilde{\sigma}B_0\bar{u}$
$\mathbf{J_q}$	heat transfer vector, W/m^2
k	fluid thermal conductivity, W/m K
K	load factor, $E_y/B_0\bar{u}$
P	pressure, N/m^2
p_x, p_y	pressure components
P_x, P_y	nondimensional pressure components
Re	Reynolds number
R_m	Magnetic Reynolds number
S_{gen}^*	nondimensional local rate of entropy generation
$\dot{S}_{gen}$	Local rate of entropy generation, W/m^3 K
T	local absolute temperature, K
T_w	wall absolute temperature, K
u	axial components of the velocity, m/s
$\bar{u}$	Mean velocity, m/s
U	nondimensional axial components of the velocity, $u/\bar{u}$
v	transverse components of the velocity, m/s
v	velocity vector, m/s
V	nondimensional transverse components of the velocity, $v/\bar{u}$
V	nondimensional velocity vector
w	velocity components in z direction
z	coordinate in the direction of the magnetic field, m
Z	nondimensional coordinate in the direction of the magnetic field, z/ H

Greek Letters

η_e	electrical isotropic efficiency or local isotropic efficiency
θ	nondimensional local absolute temperature, $(T-T_w)/(\mu\bar{u}^2)$
θ_w	nondimensional wall absolute temperature, $(kT_w/(\mu\bar{u}^2)$
μ	fluid viscosity, N s/m^2
ν	fluid specific volume, m^3/kg
∏	viscous stress tensor, N/m^2
Φ	viscous dissipation function
σ	electrical conductivity, A.m/V
$\tilde{\sigma}$	$\sigma/(1+\omega_0^2\tau^2)$, A.m/V
$\omega_0\tau$	Hall parameter
ρ	density

Subscripts

e	exit state
i	inlet state
x	x-direction
y	y-direction

tions to study the effect of the key parameters such as intensity and direction of magnetic field, the Darcy, and the Reynolds numbers on the mechanism of the convective heat transfer and flow structure. Khan et al. [12] used a mathematical model to study the effects of heat transfer on peristaltic motion of Oldroyd fluid with considering an inclined magnetic field. They showed the effect of the inclined magnetic field and some key parameters such as the wave number, the Weissenberg number, the Prandtl number and the Hartmann number on axial velocity and temperature. Zeeshan and Ellahi [13] presented the series solutions for nonlinear partial differential equations with slip boundary conditions for steady flow of a non-Newtonian and incompressible magnetohydrodynamic fluid in a pipe with porous space. In their work, they examined the effect of slip, magnetohydrodynamic, and porosity parameters. Akbar et al. [14] presented exact solutions to investigate the effect of induced magnetic field for the Brownian motion of nanoparticles in peristalsis. They graphically studied the effect of pertinent parameters such as the magnetic Reynolds number, the Grashof number, the Reynolds number, and the Strommer's number. on the profiles of pressure gradient, velocity, temperature, and induced magnetic field. Khan et al. [15] presented the Bionic study of variable viscosity on peristaltic flow of pseudo plastic fluid in an asymmetric channel in the presence of magnetic field. Ellahi et al. [16] carried out the numerical study of magnetohydrodynamics generalized couette flow of the Eyring-Powell type of the fluid considering heat transfer and slip condition. They used a hybrid technique based on the pseudo-spectral collection for solution of the problem and presented a new model. Mehrez et al. [17] studied the effect of the magnetic field on entropy generation and heat transfer considering Hartmann number, Reynolds number and Richardson number influence using the finite-volume method. Cuevas et al. [18] studied the fully-developed flow of a liquid metal in a rectangular duct of constant cross-section with a uniform, transverse magnetic field. They investigated the flow in the laminar and turbulent regimes through a composite core-side-layer spectral collocation solution even for very large Hartmann numbers in the range 10^3–10^5. Akbar et al. [19] presented an exact solution to study the influence of induced magnetic field and heat flux with the suspension of carbon nano tubes for the peristaltic flow in a symmetric channel. They graphically showed the effect of the key parameters such as the magnetic Reynolds number, Darcy number, etc. Zeeshan et al. [20] studied magnetohydrodynamic flow of water/ethylene glycol based nanofluids with natural convection through a porous medium. They obtained the analytical solutions using the homotopy analysis and presented the correlation of skin friction and heat transfer rate corresponding to active parameters. Akbar et al. [21] investigated the interaction of nanoparticle copper with the base fluid of water in an asymmetric channel considering the induced magnetic field. In this work, they presented an exact solution and discussed the variation of velocity, temperature, pressure gradient and other flow characteristics. Sheikholeslami et al. [22] used the Lattice Boltzmann Method to simulate the ferrofluid flow for magnetic drug targeting. They showed the effect of the pertinent parameters such as the Reynolds number and magnetic number on the flow characteristics. In their work they observed that the skin friction coefficient is a decreasing function of the Reynolds and magnetic numbers. Effect of Hall and ion slip on MHD peristaltic flow of a Jeffrey fluid in a non-uniform rectangular duct was investigated theoretically by Ellahi et al. [23]. The blood flow of Prandtl fluid through a tapered stenosed arteries in permeable walls with magnetic field was studied by Ellahi et al. [24]. They used the nondimensional variables to simplify the highly nonlinear equations under an assumption of mild stenosis and made an analytical computation applying perturbation method. They graphically discussed on the effects of key parameters such as impedance, slip parameter,