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Influence of a magnetic field on the energy, work, and heat flux of a multi-plate thermoacoustic system

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ABSTRACT

Research on clean and efficient energy conversion is extremely important to mitigate the high price of fossil fuel and its adverse effects on the environment. Thermoacoustic is a clean energy conversion technology that uses the conversion of acoustic to thermal energy and vice versa. However, the efficient conversion of acoustic to thermal energy using thermoacoustic systems (e.g., engine, refrigerator, or heat pump) demands research on working fluids, operational, and geometric parameters. The present study is a contribution to improve the efficiency of a thermoacoustic heat system by introducing a magnetic field perpendicular to the direction of the oscillating fluid. The major focus of this study is to examine the effect of a magnetic field on three important performance parameters: energy, heat, and work fluxes of a multi-plate thermoacoustic system. Initially, analytical expressions for the fluctuating velocity and temperature are derived from the governing continuity, momentum, and energy equations by applying the first order perturbation technique and solving these equations. The derived first order analytical equations for the fluctuating velocity and temperature enable us to calculate the energy, heat, and work fluxes and are expressed in terms of dimensionless Hartmann number (Ha_δ), temperature gradient ratio (Γ_0), Swift number (S_w), Prandlt number (Pr), and modified Rott's and Swift's parameters (f_v and f_k). It is observed that the normalized energy flux density increases with increasing Ha_δ and Γ_0 when $S_w < 1.5$. The heat flux and work flux densities also increase with increasing Ha_δ and Γ_0 when $S_w < 1.5$ and decrease when $Ha_\delta > 1.5$. The findings of this research will provide useful information to thermoacoustic system's designers for the devloepment of effieicnt magnetic thermoacoustic heat pumps.

1. Introduction

A thermoacoustic device has potential to convert temperature gradient into acoustic oscillation (i.e., the prime mover mode of operation) or acoustic oscillation into thermal gradient (i.e., the refrigerator/heat pump mode of operation) [1]. Thermoacoustics is considered as a green energy conversion technology because it uses air or inert gases as working fluids, which are benign to the environment. Several applications of thermoacoustic devices, such as, a prime mover [1,2], heat pump [3], refrigerator [1,4], heat exchanger [5], electric power generator [6], and gas mixture separator [7] are found in the literature. A typical thermoacoustic device is simple in design. It consists of a stack, two heat exchangers, and a resonant tube. The two heat exchangers are typically attached to the both ends of the stack and placed inside the resonant tube [8].

Moreover, the environmental friendly thermoacoustic prime mover or heat pump does not need any moving components, exotic materials, parts with close tolerances, sliding seal, or any critical dimensions [8]. A thermoacoustic device further can be operated using renewable and low grade energy, such as, solar energy [9] and industrial waste heat [10]. The power density of a thermoacoustic prime mover is higher than the conventional heat engine [11]. All of these advantages motivate researchers to perform further research to improve the performance (i.e., thermal efficiency, COP) of thermoacoustic devices over the years. However, thermal efficiency and COP of thermoacoustic devices are relatively lower than their conventional counterparts which is a major drawback for the utilization of thermoacoustic devices [12]. Thus, further investigation is required by focusing on the operational, geometric, and fluid parameters to enhance thermoacoustic device's performance.

The performance of a thermoacoustic system largely depends on the time phasing of the heat flow between the oscillating fluid and stack wall. A relatively smaller time phasing results in a relatively larger rate of heat transfer [13]. Such phase difference can be minimized using a transverse magnetic field [14]. Wheatley et al. [14] used an external magnetic field to control the time phase of a natural heat engine where

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Nomenclature

$\mathbf{B}$	magnetic induction, Wb·m^{-1}
C_p	specific heat of the fluid at constant pressure, Jkg^{-1} K^{-1}
c_m	Sound velocity, m·sec^{-1}
DR	drive ratio, $(=p_1/p_m)$
$\dot{\mathbf{E}}$	energy flux density vector, W·m^{-2}
$\dot{E}_2$	second order energy flux density, W·m^{-2}
f	frequency of oscillation, Hz
f_v	first Rott's function of thermoacoustics, $=(\tanh[(1+i)\sqrt{1+Ha_\delta^2/2i}\ S_w])/((1+i)\sqrt{1+Ha_\delta^2/2i}\ S_w)$
f_k	second Rott's function of thermoacoustics, $=(\tanh[(1+i)\sqrt{\Pr}\ S_w])/((1+i)\sqrt{\Pr}\ S_w)$
Ha_δ	Hartmann number, $(=B_y\delta_\nu\sqrt{\sigma/\mu})$
h	enthalpy, J·kg^{-1}
i	complex number, $(=\sqrt{-1})$
$\mathbf{J}$	current density, amp·m^{-2}
k	thermal conductivity, Wm^{-1} K^{-1}
k_0	ratio of sound velocity and angular frequency, $=c/\omega$
L	length of stack, m
Ma	Mach number,
P	pressure, N·m^{-2}
Pr	Prandtl number of the fluid, $=\delta_\nu{}^2/\delta_k{}^2$
$\dot{Q}_2$	heat flux, (W).
S_w	Swift number, $=y_0/\delta_\nu$
$\overline{S}_w$	modified swift number, $=y_0/\delta_k$
t	time, s
T	temperature of the fluid, K
$\mathbf{v}$	velocity vector, m·sec^{-1}
u	axial velocity component, m·sec^{-1}
v	transverse velocity, m·sec^{-1}
$\dot{W}_2$	work flux, (W).
x	axial distance, m
x_s	starting point of the stack, m
x_e	ending point of the stack, m
y	transverse distance in fluid, m
y_0	half channel width, m
Y	dimensionless transverse distance, $=y/y_0$

Greek symbols

α_f	thermal diffusivity of the fluid, $=k/\rho_f C_p$
β	thermal expansion coefficient, K^{-1}
δ_ν	viscous penetration depth, $=\sqrt{2\nu/\omega}$
δ_k	thermal penetration depth, $=\sqrt{2\alpha_f/\omega}$
μ	dynamic viscosity of the fluid, N·m^{-2}·sec
μ_0	permeability of the free space $=4\pi\times10^{-7}$ Wb amp^{-1} m^{-1}
ν	kinematic viscosity, m^2·sec^{-1}
$\boldsymbol{\sigma}$	viscous stress tensor, N·m^{-2}
σ	electrical conductivity of the fluid, Ω^{-1}·m^{-1}
ω	circular frequency, rad·sec^{-1}
ρ	density of the fluid, kg·m^{-3}
τ	time period, $=2\pi/\omega$
∇p	pressure gradient, N·m^{-3}
∇T_m	mean temperature gradient, $=\partial T_m/\partial x$
∇T_{cr}	critical temperature gradient, K·m^{-1}
Γ_0	temperature gradient ratio, $=\nabla T_{cr}/\nabla T_m$
Γ_{cond}	ratio of axial conduction to reference global energy flux, $=\Pi y_0 k\nabla T_m/E_0$
γ	specific heat ratio, $=C_p/C_v$
λ	wavelength, m
Φ	viscous dissipation function
Π/2	stack plate width, m

Subscripts, superscripts, and symbols

1	first order variable
∞	free stream value
m	mean value
r	reference value
~	complex conjugation
$\Re[\ ]$	real part of an expression
$\Im[\ ]$	imaginary part of an expression

liquid sodium was used as a working fluid. Afterwards, a very few number of articles were published that considered the improvement of thermoacoustic prime mover/refrigerator using an external magnetic field. Mahmud and Fraser [15] developed analytical models of a single plate thermoacoustic system to investigate the influence of a magnetic field on heat flux, work flux, and the operating conditions. They further estimated the heat transfer by incorporating magnetic field perpendicular to the direction of oscillating fluid flow in a porous stack. Mahmud and Fraser [15] found that addition of magnetic field was capable of enabling larger stack dimensions and hence enhanced heat transfer rate from the stack element. In turn, larger stack dimensions are useful for improving heat exchanger efficiency, thus improving overall thermoacoustic system efficiency when a magnetic field was placed perpendicular to the direction of flow. Many reported studies extensively examined the performance of thermoacoustic devices by changing the stack geometry [12,15–25], resonance tubes [26–27,32,34], acoustic pressure amplifier and loudspeaker [28,35], working fluids [29–30], operating conditions [30,33] and heat exchangers [5,31]. However, none of the above mentioned study considered the effect of a transverse magnetic field on the performance of a multi-plate thermoacoustic device which motivated us to conduct a study on a multi-plate thermoacoustic system due to the presence of a transverse magnetic field.

Recently, Islam et al. [36] developed theoretical models to analyze the influence of a transverse magnetic field on a thermoacoustic system where porous stack is attached with a thick solid plate. Islam et al. [36] observed that the critical temperature gradient can be controlled by changing the transverse magnetic field. Therefore, the transverse magnetic field can be used to determine the thermoacoustic modes of operation which supports Mahmud's and Fraser's [15] findings. The heat flux increases and the work flux decreases with increasing the value of magnetic field. The thermal efficiency is maximum when the critical temperature gradient approaches to mean temperature gradient.

The literature survey shows that Islam et al. [13] is the only study that considered a transverse magnetic field to develop analytical models to calculate complex Nusselt number of a multi-plate thermoacoustic system. The current research is an extension of Islam et al.'s [13] work with a goal to study the effect of the magnetic field on the heat flux, work flux, and energy flux densities of a multi-plate thermoacoustic system, that have not been studied in Islam et al. [13]. Such a study will offer insight into ways to increase the energy conversion efficiency of a multi-plate magnetic thermoacoustic heat pump and will ultimately help the scientific community design better thermoacoustic systems.

2. Problem formulation

In the current study, a two-dimensional, unsteady-state, and compressible fluid is considered flowing through a parallel-plate channel. Fig. 1(a) presents the schematic diagram of the proposed thermoacoustic system. The acoustic driver is placed at the open end of the