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Heat transfer enhancement by induced vortices in the vicinity of a rotationally oscillating heated plate

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ABSTRACT

The present study is conducted to investigate the flow field and its impact on the thermal characteristics in the immediate surroundings of a rectangular flat plate, subjected to rotational oscillations in a quiescent fluid. The plate is heated with a constant heat flux on both faces during its rotational motion about one of its edges. The induced flow and thermal characteristics were simulated experimentally and computationally using the dynamic mesh method. The flow around a fabricated laboratory model was visualized with smoke particles and the surface temperature was recorded using J-types thermocouples. During the plate's flapping cycles, computational and experimental results exhibit the presence of strong vortices near the free edges. When shed off, these vortices participate significantly in the enhancement of the cooling rate of the heated surface. The time dependent surface temperature distribution is symmetrical and characterized by a transient unsteady periodic variation which precedes a steady periodic phase. The results of current investigations present an interest in the cooling of portable electronic devices and shed light in the elephant's metabolic heat regulation by the flapping of its pinnae.

1. Introduction

Although interest in oscillating flows dates back to the mid-19th century [1,2], literature search indicates that this problem has not been completely investigated. Inspired by the flapping flight of insects [1–7] and birds [8], the swimming of aquatic animals [9–11] and the metabolic heat dissipation by large animals [12], the study of rotational oscillating plates is motivated by the development of new techniques of locomotion [13–15] and heat transfer enhancement [16,17]. However, the transient nature of the flow around flapping wings involves complex vortex shedding and interaction which are difficult to analyze [18,19]. Licht et al. [20] used flapping foils of 0.1 m × 0.4 m driven by actuators to design an underwater vehicle. It has been found that the rotational oscillating motion of the surface provided thrust for the propulsion of the vehicle. In their investigation of propulsive oscillating foils, Guglielmini et al. [21] explained the thrust produced in the locomotion of the fish as generated by vortices that shed in the opposite direction of the forward motion. Lee et al. [22] investigated experimentally the force production mechanism of swimming and flying; they observed by flow visualization, the development of two independent vortical structures in each half cycle, which occurred during the acceleration and the stroke reversal phases. Fu et al. [23] studied experimentally the aerodynamics of bio flyers using three rectangular wings with different aspect ratios subjected to sinusoidal kinematics. They found a strong K-H instability in the flow field which led to vortex bursting [23]. Similarly, Pierides et al. [24] studied experimentally the flow around square and triangular actuators panels mounted on the wall of a wind tunnel, impulsively rotated with low angular velocity from rest, in the presence of an existing free stream. It has been found that the free stream mixes with the flow induced by the rotating panel, creating vortical structures which participate in the enhancement of transient aerodynamic forces on the plate's surface. These studies, relevant to the understanding of the aerodynamics of natural flyers give important insight on force production by rotationally oscillating plates [24–30]. They are not concerned about the thermal characteristics induced by the motion of the rotating devices.

Many experimental investigations in biology revealed that the rotational oscillating motion of a hot surface can enhance heat dissipation from the surface by convection [31–38]. Ward et al. [39] used infrared thermography to measure the temperature of starlings flying in a wind tunnel with a free stream velocity ranging from 6 to 14 m/s and an ambient temperature between 15 °C and 25 °C. Calculated heat transfer coefficients for the 14 sections of the bird's surface indicate highest values from the wing as a result

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Nomenclature

f_c	cut off frequency, Hz
f_p	fundamental frequency of the oscillation, Hz
Gr	Grashof number
k	turbulence kinetic energy
L	characteristics length, m
p	fluid pressure, Pa
$\bar{p}$	average fluid pressure, Pa
q^{Prime}	heat flux, W/m^2
r	radial coordinate, m
Re_L	Reynolds number
St_l	Stokes number
t	time, S
T	surface temperature, °C
T_{rec}	reconstructed temperature signal, °C
T_{LP}	long-time trend of surface temperature, °C
T_{HP}	high frequency content of the temperature variations, °C
u_{bn2}	moving body velocity, m/s
$\bar{u}_i$, $\bar{u}_j$	average flow velocity, m/s
u'_i, u'_j	fluctuating terms of flow velocity, m/s
U_o	reference velocity, m/s
Ut	tip velocity, m/s
w	velocity in the z-direction
W	characteristics length along radius, m
(x_j,x_j,x_j)	Cartesian coordinate system in indicial notation
(x,y, z)	Cartesian coordinate system

Greek letters

δ_a	boundary layer thickness, m
δ_{ij}	Kronecker delta
ε	dissipation rate
μ	dynamics viscosity, kg/s m
μ_T	enhanced turbulent viscosity, kg/s m
ν	kinematics viscosity, m/s^2
ν_T	kinematic eddy viscosity
π_{ij}	stress tensor
ρ	fluid density, kg/m^3
σ_k	normal stress tensor component in the z direction
Ω_x	vorticity in x-direction, 1/s
Ω_z	vorticity in z-direction, 1/s
Φ	general dissipation function expressed in Cartesian coordinates
ω	frequency of oscillations, rad/s

of heat transfer enhancement due to its flapping motion. In these studies, conducted with infrared thermography, no description of the unsteadiness of the flow is provided. Therefore, its influence on the temperature distribution is unknown. Furthermore, the tracking of the transient surface temperature data over several oscillations of the flapping device is not available. Experiments performed by Datta [40] on African elephants showed that these animals use both sides of their pinnae as fins to dissipate significant amount of metabolic heat. According to his study, flapping increases heat loss due to an increase in air flow. Phillips and Heath [41] used infrared thermography to scan the pinnae of four female zoo elephants for the measurement of instantaneous heat loss. In their investigations, they built a flat plate model to estimate the heat loss in terms of the wind velocity at different ambient conditions. They found that the heat loss from the ear is enhanced by its motion, nevertheless the temperature distribution across the elephant ear depends on ambient conditions [41]. In this work, the measurement of the surface temperature of a moving pinna was difficult to achieve due to the transient nature of its motion. Focusing on the ear of the elephant, a recent study by Koffi et al. [42] designed a flapping mechanism for the experimental investigation of the flow induced by the rotational oscillating motion of fabricated laboratory models of elephant ears. Their computational and experimental results showed the presence of tip vortices which explains the heat transfer enhancement at these locations by forced convection. They found that the shedding vortices from the surface of the flapping ear model at end cycles interact with the boundary layer of the model improving the heat dissipation rate from the surface.

In most applications involving rotational oscillatory motion of a flat panel, a non-stagnate environment already exists in the flow, which subsequently mixes with the flow induced by the moving device. In that respect, the present study focuses on the case where the motion of the fluid is originated by the rotational oscillatory motion of the plate, in the absence of free stream. The physical model used, shown in Fig. 1, is a rectangular flat plate of width and length W and L respectively which oscillates with an angular frequency, ω. One of the challenges in the study of such flows is

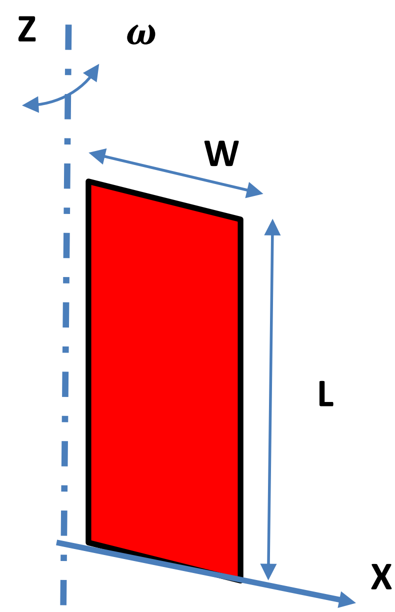

Fig. 1. Schematic of a rotationally oscillating rectangular flat plate.

their highly unsteady nature. The generation of vorticity at the moving solid wall and the subsequent formation of vortices play a critical role in the plate's surface temperature spatial and temporal distribution. The interaction of these vortices with the near wall boundary layer on the plate's surface is expected to increase the cooling rate of the moving surface by forced convection. However, the dynamics of this interaction is not well understood and details of how these vortices, generated during strong accelerations of oscillating heated surfaces, affect the distribution of the local surface temperature, are not known. The current experimental and computational study is designed to investigate the impact of induced vortices on the thermal characteristics of the moving object's surface.