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Temperature-aware time-varying convection over a duty cycle for a given system thermal-topology

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ABSTRACT

Smart dynamic thermal management (SDTM) is a key enabling technology for optimal design of the emerging transient heat exchangers/heat sinks associated with advanced power electronics and electric machines (APEEM). The cooling systems of APEEM undergo substantial transition as a result of time-varying thermal load over a duty cycle. Optimal design criteria for such dynamic cooling systems should be achieved through addressing internal forced convection under time-dependent heat fluxes. Accordingly, an experimental study is carried out to investigate the thermal characteristics of a laminar fully-developed tube flow under time-varying heat fluxes. Three different transient scenarios are implemented under: (i) step; (ii) sinusoidal; and (iii) square-wave time-varying thermal loads. Based on the transient energy balance, exact closed-form relationships are proposed to predict the coolant bulk temperature over time for the aforementioned scenarios. In addition, based on the obtained experimental data and the methodology presented in Fakoor-Pakdaman et al. (2014), semi-analytical relationships are developed to calculate: (i) tube wall temperature; and (ii) the Nusselt number over the implemented duty cycles. It is shown that there is a 'cut-off' angular frequency for the imposed power beyond which the heat transfer does not feel the fluctuations. The results of this study provide the platform for temperature-aware dynamic cooling solutions based on the instantaneous thermal load over a duty cycle.

1. Introduction

Smart dynamic thermal management (SDTM) is a transformative technology for efficient cooling of advanced power electronics and electric machines (APEEM). APEEM has applications in: (i) emerging cleantech systems, e.g., powertrain and propulsion systems of hybrid/electric/fuel cell vehicles (HE, E, FCV) [1,2]; (ii) sustainable/renewable power generation systems (wind, solar, tidal) [3,4]; (iii) information technology (IT) services (data centers) and telecommunication facilities [5–7]. The thermal load of APEEM substantially varies over a duty cycle; Downing and Kojasoy [8] predicted heat fluxes of $150-200\ [\mathrm{W/cm^2}]$ and pulsed transient heat loads up to $400\ [\mathrm{W/cm^2}]$, for the next-generation insulated gate bipolar transistors (IGBTs). The non-uniform and time-varying nature of the heat load is certainly a key challenge in maintaining the temperature of the electronics within its safe and efficient operating limits [9]. As such, the heat exchangers/heat sinks associated with APEEM operate periodically over time and never attain a steady-state condition. Conventionally, cooling systems are conservatively designed for a nominal steady-state or worst-case scenarios, which may not properly represent the thermal behavior of various applications or duty cycles [10]. The state-of-the-art approach is utilizing SDTM to devise a variable-capacity cooling infrastructure for the next-generation APEEM and the associated engineering applications [7]. SDTM responds to thermal conditions by adaptively adjusting the power-consumption profile of APEEMs on the basis of feedback from temperature sensors [5]. Therefore, supervisory thermal control strategies can then be established to minimize energy consumption and safeguard thermal operating conditions [9]. As such, the performance of transient heat exchangers is optimized based on the system "thermal topology", i.e., instantaneous thermal load (heat dissipation) over a duty cycle. For instance, utilizing SDTM in designing the cooling systems of a data center led to significant energy saving, up to 20%, compared to conventionally cooled facility [7]. In addition, in case of the HE/E/FCV, SDTM improves the vehicle overall efficiency, reliability and fuel consumption as well as reducing the weight and carbon foot print of the vehicle [11].

Therefore, there is a pending need for an in-depth understanding of instantaneous thermal characteristics of transient cooling systems over a given duty cycle. However, there are only a few analytical/experimental studies in the open literature on this topic.

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Nomenclature

a	heat flux amplitude, [W/m^2]
c_p	heat capacity, [J/kg/K]
c_n	coefficients in Eq. (10)
D	tube diameter, [m]
Fo	Fourier number, $= \alpha t/R^2$
h	heat transfer coefficient, [W/m^2/K]
J	Bessel function
k	thermal conductivity, [W/m/K]
L	length, [m]
m	integer number, Eq. (21)
$\dot{m}$	mass flow rate, [kg/s]
Nu_D	local Nusselt number, $= [h(x,t) \times D]/k$
$\overline{Nu_D}$	average Nusselt number, $\frac{1}{L_2}\int_0^{L_2} Nu_D dx$
P	power, [W]
p	period of the imposed power, [s]
Pr	Prandtl number, $= \nu/\alpha$
q''	thermal load (heat flux), [W/m^2]
R	tube radius, [m]
r	radial coordinate measured from tube centerline, [m]
Re	Reynolds number, $= UD/\upsilon$
T	temperature, [K]
t	time, [s]
U	velocity, [m/s]
X	dimensionless axial distance, $= 4x/\mathrm{Re}\cdot\mathrm{Pr}\cdot D$
x	axial distance from the entrance of the heated section, [m]

Greek letters

α	thermal diffusivity, [m^2/s]
ν	kinematic viscosity, [m^2/s]
ρ	fluid density, [kg/m^3]
λ_n	Eigenvalues in Eq. (10)
Λ_n	values defined in Eq. (10)
θ	dimensionless temperature, $= \frac{T-T_{in}}{q_r''D/k}$
Ψ	a function defined in Eq. (23)
Υ	a function defined in Eq. (18)
β_n	positive roots of the Bessel function, $J_1(\beta_n) = 0$
ω_1	angular frequency of the sinusoidal heat flux, $= (2\pi R^2)/(p_1\alpha)$
ω_m	dimensionless number characterizing the square-wave heat flux, $= [(2m+1)\pi R^2]/(p_2\alpha)$

Subscripts

1	sinusoidal scenario
2	square-wave scenario
in	inlet
m	mean or bulk value
out	outlet
r	reference value
w	wall

This study is focused on transient internal forced convection as the main representative of the thermal characteristics of dynamic heat exchangers under arbitrary time-varying heat fluxes. In fact, such analyses lead to devising "temperature-aware" cooling solutions based on the system thermal topology (power management) over a given duty cycle. The results of this work will provide a platform for the design, validation and building new smart thermal management systems that can actively and proactively control the cooling systems of APEEMs and similar applications.

1.1. Present literature

Siegel [12–17] pioneered study on transient internal forced-convective heat transfer. Siegel [12] studied laminar forced convection heat transfer for a slug tube-flow where the walls were given a step-change in the heat flux or alternatively a step-change in the temperature. Moreover, the tube wall temperature of channel slug flows for particular types of position/ time-dependent heat fluxes was studied in the literature [17,18]. Most of the pertinent literature was done for laminar slug flow inside a duct. The slug flow approximation reveals the essential physical behavior of the system, while it enables obtaining exact mathematical solution for various boundary conditions. Using this simplification, one can study the effects of various boundary conditions on transient heat transfer without tedious numerical computations [12,15]. Siegel [15] investigated transient laminar forced convection with fully developed velocity profile following a step change in the wall temperature. The obtained solution was much more complex than the response for slug flow which was presented in [12]. It was reported that the results for both slug and fully-developed flows showed the same trends; however, the slug flow under-predicted the tube wall temperature compared to the Poiseuille flow case. Fakoor-Pakdaman et al. [19–22] conducted a series of analytical studies on the thermal characteristics of internal forced convection over a duty cycle to reveal the thermal characteristics of the emerging dynamic convective cooling systems. Such thermal characteristics were obtained for steady slug flow under: (i) dynamic thermal load [19,20]; (ii) dynamic boundary temperature [21]; and (iii) unsteady slug flow under time-varying heat flux [22]. Most literature on this topic is analytical-based; a summary is presented in Table 1.

Table 1
Summary of existing literature on convection under dynamically varying thermal load.

Author	Notes
Siegel [12]	✓ Reported temperature distribution inside a circular tube and between two parallel plates × Limited to step wall heat flux × Limited to slug flow condition × Limited to an analytical-based approach without validation/verification
Siegel [15]	✓ Reported temperature distribution inside a circular tube or between two parallel plates ✓ Covered thermally developing and fully-developed regions ✓ Considered fully-developed velocity profile × Limited to step wall temperature × Nusselt number was defined based on the tube wall and inlet fluid temperature × Limited to an analytical-based approach without validation/verification
Fakoor-Pakdaman et al. [20]	✓ Reported temperature distribution inside a circular tube ✓ Defined the Nusselt number based on the tube wall and fluid bulk temperature × Limited to slug flow condition × The analytical results were only verified numerically
Fakoor-Pakdaman et al. [22]	✓ Reported temperature distribution inside a circular tube ✓ Considered transient velocity profile for the fluid flow × Limited to sinusoidal wall heat flux. × The analytical results were only verified numerically