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Research paper

Compact thermal modeling methodology for predicting skin temperature of passively cooled devices

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HIGHLIGHTS

- A resistor–capacitor (RC) thermal model for predicting surface temperature of passively cooled devices was developed.
- It was found that RC-thermal coefficients pertinent to passive systems are power dependent.
- An alternative numerical solution was developed to address non-linearity in natural convection and radiation problems.

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ABSTRACT

Compact thermal modeling of microelectronic systems has recently attracted considerable attention. The present work aims at developing resistor-capacitor (RC) thermal models for predicting time-dependent surface temperature of a passively cooled device. The developed models mimic typical fanless systems cooled by dissipating heat to the surroundings through the enclosure back case by natural convection and radiation. In order to establish a baseline for checking the accuracy of the compact thermal model, the same problem was modeled using three-dimensional, transient, Navier–Stokes equations that were solved numerically by computational fluid dynamics (CFD) code. For constructing Foster RC-network ladders and to find best-fit thermal constants, temperature step responses of the hot-spot were obtained by applying known power pulses on the discrete heat source. Special attention was paid to the characteristics of the RC-network ladders for obtaining a reasonably accurate numerical scheme for real-time calculation of hot-spot surface temperature. In the present study it is demonstrated that the thermal constants (R, τ) are strong functions of the input power. An alternative usage of formulation for multi-ladder Foster RC-network, incorporating time-dependent thermal constants is show-cased. The suggested methodology can be used for non-linear problems involving time- and power-dependent boundary conditions.

1. Introduction

The growing consumer demand for increased mobility, connectivity, computation, vision, and advanced features have resulted in highly integrated system solutions. Advancements in process technology continue to deliver smaller, faster, and lower cost system-on-a-chip (SoC) solutions, introducing significant thermal challenges [1–3].

Performance of thin-profile mobile form factors such as tablets and ultra-thin laptops are limited primarily due to ergonomic requirements [4,5]. Systems are designed to meet specific ergonomic requirements so that they satisfy user experience. In designing hand-held systems, power dissipation of the SoC is controlled such that the system does not exceed the required skin temperature limits. Ergonomic requirements make temperature-aware power control a necessary mechanism for achieving close to optimal device performance.

Temperature aware power management algorithms have existed for more than a decade. Fig. 1 shows a simplified flowchart of a power management algorithm that takes into account device temperature when making decisions on device power levels. An example architecture is implemented in the Dynamic Power and Thermal Framework (DPTF) algorithm [6,7]. The algorithm makes use of temperature sensors for determining thermal headroom for SoC to increase its power. Implementation

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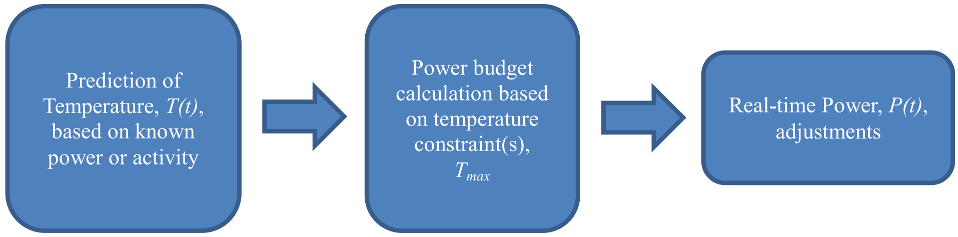

Fig. 1. Temperature prediction and power budget assignment.

of direct temperature sensing methods by thermal diode, thermopile, ring-oscillator, or infrared radiation techniques has often proven impractical due to cost, accuracy, and production complexity considerations.

As an alternative to the direct temperature measurement methods, compact thermal models can be utilized. Compact thermal models require power as an input, which can be available by direct current measurement or monitoring activity via capacitance. The challenge then becomes dealing with efficiency and accuracy of the power management algorithm which, in effect, is directly dependent on the precision of the thermal model used for predicting temperature. Touzelbaev et al. [8] and Yang et al. [9–11] used Foster thermal RC-networks for compact modeling of transient heat conduction in packages. Their goal was to answer fundamental reliability questions in package production operations. A formulation using recursive Infinite Impulse Response (IIR) method was developed for approximating device temperature response in time based on constant time steps by assuming linear or step-variation of power during each time step. The methodology developed assumed constant heat transfer coefficient, h, on top of the package resembling a heat-sink. Several RC ladders were placed in series forming a lengthy network. For mathematically representing the RC-network as a ladder Szekely's method [11–13] was adopted leading to a network consisting of ten ladders in series to resolve die-level temperature fluctuations at reasonable accuracy. The developed methodology was proven to be accurate through comparison with CFD simulations.

Other researchers have also adopted de-convolution techniques and simplified numerical models for package-level heat conduction modeling. Sofia [14], Schweitzer [15], and Gerstenmair and Wachutka [16] are few to name who adopted de-convolution algorithms for solving thermal problems using RC-network representation. Ishizuka [17–19], developed a thermal RC-model based on simplified heat transfer equations by including natural convection and radiation at the boundary of the solution domain. In their model, thermal capacitance was set to a constant value. Natural convection phenomenon was modeled based on available textbook flat-plate correlations.

In this work usage of thermal RC-networks is further extended to non-linear systems. The researchers reviewed modeled transient evolution of temperature in linear systems, i.e., assumed unchanging boundary conditions and thermal constants. The present work aims at deriving a compact thermal model using Foster thermal RC-circuit network for representing non-linear natural convection and radiation problems. The non-linearity of the problem is due to the power-dependent boundary condition; with increasing power both buoyancy and radiation effects are enhanced resulting increased heat transfer coefficient, h, at higher powers. An example practical problem that resembles a hand-held low-power system was selected to demonstrate the methodology as well as the formulation. The goal of the present study is two-folds:

- Finding optimum number of RC-network ladders needed for resolving transient natural convection and radiation around a plate subjected to a discrete heat source at its internal boundary
- Deriving an explicit, numerical model that discretizes the RC-network in time and one that accounts for variable thermal coefficients.

2. Geometry and boundary conditions

Fig. 2(a) demonstrates a typical tablet system showing cross-section and mechanical stack-up including the LCD, top glass, battery, PCB, processor, and the chassis side wall. A zoom-in model section of the chassis mainly including the processor and the outer boundary is shown in Fig. 2(b). While the zoom-in model is a good representation of the region of interest, it was further simplified to a plate heated by a discrete heat source, Fig. 2(c). This simplification further eliminates complexities associated with geometry and material properties of the components other than the heat source and the heat dissipation medium.

Immediately after a power pulse is applied by the processor and once the heat wave travels through the thickness of the tablet reaching the system boundary, air starts ascending at the vicinity of the wall due to the change in density gradients (i.e., natural convection) and the system starts radiating thermal energy to the surrounding air particles. The movement of air forms a thermal boundary layer around the outer surface of the device. Next section discusses the numerical solution used for resolving fluid flow and heat transfer around the plate.

3. Three-dimensional, transient finite volume numerical solution

The plate problem qualitatively represents a hand-held tablet system's back side chassis exposed to ambient air. The goal of this study is to replace more complex and time-consuming CFD computations with compact models to significantly simplify the computations. The system thermo-physical characteristics are shown in Table 1.

3.1. Navier–Stokes equations

Model equations are described in [21,20]. The geometry of the problem modeled together with boundary conditions is shown in Fig. 3. For the fluid, the governing equations are the continuity, momentum, and energy equations, respectively representing laminar flow:

$$\nabla \cdot \nu = 0 \tag{1}$$

$$\rho_f \left[\frac{\partial \nu}{\partial t} + (\nu \cdot \nabla)\nu \right] = -\nabla p + \mu \nabla^2 \nu + \rho_f g \beta (T - T_c) j \tag{2}$$