Integrated Simulation Toolkit for Electronic Controlled Motor System

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ABSTRACT: The purpose of this study is to establish an analytical-numerical hybrid technique for system-wide thermal modeling of electronic controlled motors. The thermal models are fully coupled with electronic network model, which makes the simulation more close to real working conditions. It employs finite volume concept to handle heat conduction in solid media and adopts analytical equations to calculate velocity and temperature profiles for convection of fluid flow. The experimental data from various tested motors showed that a good accuracy could be reached by using much less time and effort compared to the numerical simulation, such as FVM or FEA. Simplicity, ease-of-use, coupled with electronic signal models, and moderate accuracy make this research attractive in solving complicated electrical-thermal systems. The model can be used not only for rapid thermal evaluation in early design stage, but also for detailed system-physical simulation.

1 INTRODUCTION

As electronic products shrinking in size and requiring high reliability in harsh environment, thermal issues stand out in all levels of electronic product development. In order to meet thermal management challenges and accelerate the design-market deliver cycle for the next generation electronic controlled motors, there is a need to study fully coupled thermal-electrical characterization by using integrated simulation tools.

Many computational fluid dynamics (CFD) and finite element analysis (FEA) software packages are available to simulate heat transfer through solid media and fluid flow. However, none of them can be coupled with circuit simulation. Moreover, even with latest computing power, these simulations are still time-consuming in terms of geometry modeling, computing, calibration, and experimental support (Igic et al. 2001, Kraus et al. 1983). This research employs finite volume method (FVM) concept to calculate heat conduction for motor components while using flow network modeling for fluid convection calculation. Flow network modeling (FNM) is a method that representing the overall flow system as a network of components and flow paths to calculate flow rates and temperature profiles (Belady et al. 1999, Minichiello 2000). Analytical functions for certain flow patterns, such as pipe flow and internal/external natural convection flow, are used to predict the thermal performance over the flow network (Rohsenow 1998). FNM is able to analyze system-level interaction of the individual components in a rapid and accurate manner. This analytical-numerical hybrid scheme (FNM-FVM) not only simplifies the complicated flow simulation but also considers motors' geometry information and increases the accuracy of the simulation.

The research is to build a suite of tools and methodology to assess thermal issues at all stages of design from concept through application. Because the systems are applied under a large range of external conditions (temperature, cooling airflow rate and mechanical and electrical load) an analytical-numerical hybrid thermal management system for complex electronic-mechanical system is established. The simulation process is capable of modeling steady state and transient thermal issues within the system, including conduction from electronic and mechanical components to the convecting surfaces, natural convection, radiation, and mass flow heat absorption. Electronic control signals for motor performance are handled using separate time integration scheme. Coupled thermal effects for various electronic properties and electrical generated heat losses are considered through thermal-electronic interface during computation.

Software package Saber (by Avanti software) for mixed domain network analysis is selected to implement the system simulation model. Three-dimensional CFD simulations are performed to study the different environmental variables that dictate the heat transfer behavior. Combined with the experimental data, these simulation results are used to calibrate network models that capture all of the physics (Kang 2000). Complexity rises dramatically as more details are being considered in the thermal network topology and electronic system. In order to cope with this situation, a thermal block based on the control element concept of finite volume method is adopted, which considers heat conduction, heat source, and heat capacitance. Blocks can be assembled to form components and further connected to a higher-level hierarchy. Combined with a convection network and motor control section, the model can simulate complex thermal behaviors with the flexibility to optimize shape, materials, and performance during design stage.

In fact, one of the model's advantages is the ability to quickly generate new system models for each design, which may otherwise take a long time to develop. Various physical arrangements of electronic board are tested based on this simulation toolkit and results showed significant system effects on the thermal behavior. Further development is to build a user-friendly GUI (graphical user interface) that encapsulates detailed Saber programming from designers and integrate motor models into higher-level system models - such as the entire car, while still accurately capture the thermal characteristics.

2 THERMAL ELEMENT

A hierarchy of thermal component topology has been developed to deal with the complexity raised as more details are considered. The basic component is a heat conduction block, which considers heat conduction, heat source, and heat capacitance. The block links with other elements via its thermal connection pins. More blocks can be assembled to form a certain part. Furthermore, combining with fluid network and motor performance models, parts can be assembled to form a whole motor system.

2.1 *Heat conduction block*

The approach is based on the control block concept of finite volume method. The cylindrical thermal conduction block is used during the current simulation, shown as Figure 1. However, other geometry, such as one or two dimensional block, three-dimensional rectangular cube, and spherical block can also be constructed using the same principle (Anderson et al 1984).

Heat transfer is by conduction in solid, where $c_v \approx c_p$.

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\dot{q}}{\rho c_p}, \qquad \alpha = \frac{k}{\rho c_p} \tag{1}$$

where k is constant and may varied with direction. $\dot{q}$ is heat source and α is thermal diffusivity. For cylindrical thermal conduction block, the discrete form of heat conduction formula is shown as below:

$$
\begin{aligned}
&k\frac{(r-\Delta r/4)\Delta\phi\Delta z}{\Delta r/2}\left[T_a - T_{center}\right] + k\frac{(r+\Delta r/4)\Delta\phi\Delta z}{\Delta r/2}\left[T_b - T_{center}\right] + \\
&k\frac{\Delta r\Delta z}{r\Delta\phi/2}\left[T_c - T_{center}\right] + k\frac{\Delta r\Delta z}{r\Delta\phi/2}\left[T_d - T_{center}\right] + \\
&k\frac{r\Delta r\Delta\phi}{\Delta z/2}\left[T_e - T_{center}\right] + k\frac{r\Delta r\Delta\phi}{\Delta z/2}\left[T_f - T_{center}\right] + \dot{q}r\Delta r\Delta\phi\Delta z \\
&= \left[\frac{\rho c_p T_{center}\,|_{t+\Delta t} - \rho c_p T_{center}\,|_t}{\Delta t}\right] r\Delta r\Delta\phi\Delta z
\end{aligned} \tag{2}
$$

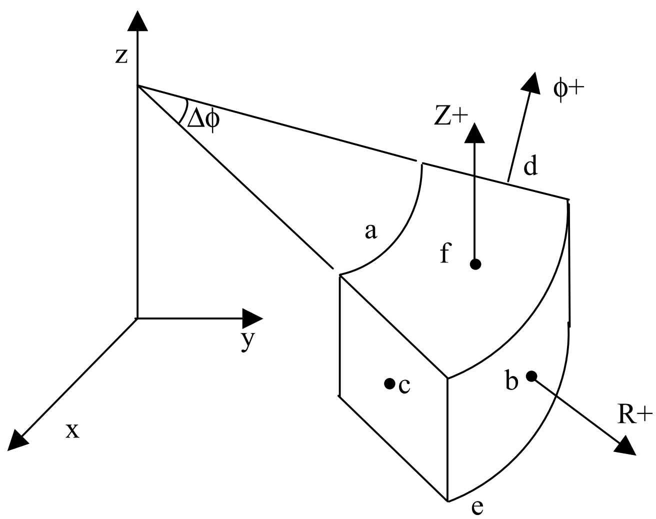


Figure 1. Cylindrical thermal conduction block with six thermal pins on the surfaces.

2.2 *Convection flow pipe*

Forced convection scheme is based on thermal and hydrodynamic boundary layer theory. The exact analytical solution for laminar flow over a flat plate is expressed as:

$$Nu_L = 0.664 \cdot \Pr^{1/3} \cdot \mathrm{Re}^{1/2} \tag{3}$$

where Pr is Prandl number, Re is Reynolds number, and Nu_L is Nusselt number for laminar flow. The natural convection Nusselt number can be expressed as:

$$Nu_N = C \cdot (Gr \cdot \Pr)^m \tag{4}$$

where C and m are empirically determined for different geometry, Gr is Grashof number related to the strength of the buoyancy force to the viscous force in the natural convection system (Bar-Cohen 1998). Mixed convection is used when $Gr/Re^2 \approx 1$. The motor geometry effects and rotor rotation are also considered when implementing detailed flow pipe formula (Booth 1999). Figure 2 is a flow pipe system for water pump electronic controlled motor. The flow pipe element has velocity and temperature pins that are connected to the other thermal components. Many other basic thermal elements have been developed, such as contact surface element, radiation element, *etc*.

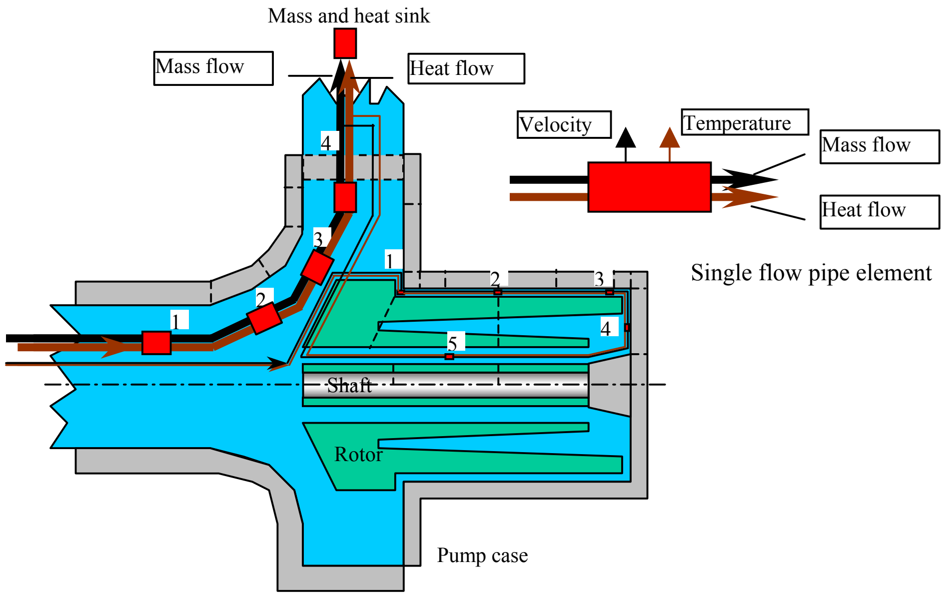


Figure 2. Flow pipe element and flow pipe system for water pump electronic controlled motors.

3 MODEL GENERATION

Cylindrical and rectangular thermal conduction blocks are used to form water pump motor parts combined with fluid flow network and motor performance Saber models, as shown in Figure 3. Different grayscale represents different motor part. Some parts are simplified in the figure for clarity. The dark lines between liquid and motor parts are layers where motor parts are in contact with the coolant and where, consequently, the convection coefficient for forced convection is calculated.

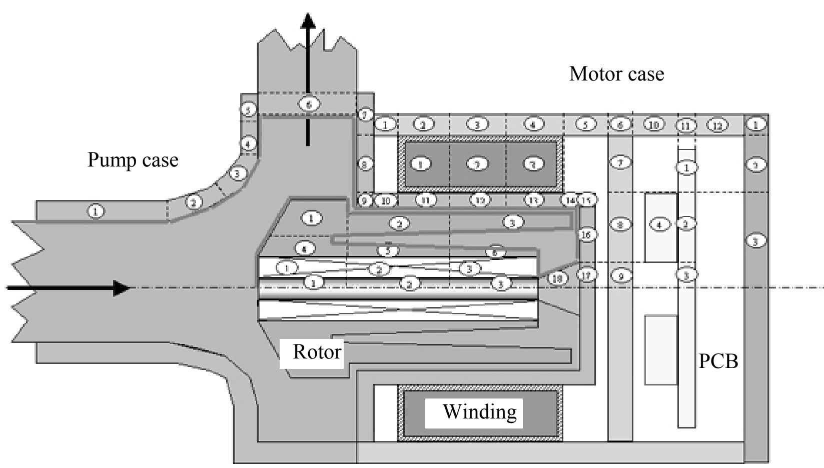


Figure 3. Thermal network model for water pump motors.

A component layer thermal wrapper has been developed in Saber Templates to go between potentially detailed internal models of components, PCB, natural convection, heat sinks and the interface to motor case, shown in Figure 4. Designer has flexibility to lay out electronic components in any location and the wrapper model will take care of the thermal issues.

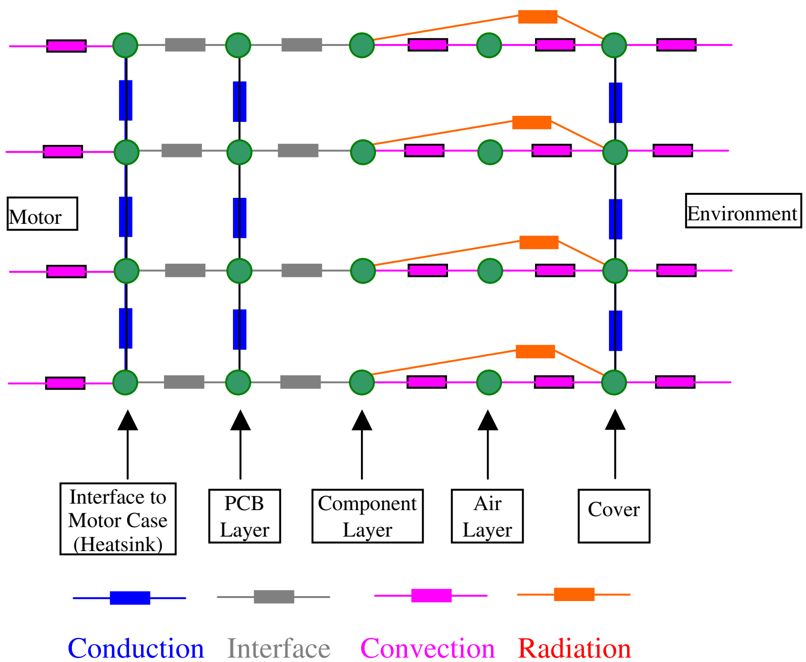


Figure 4. Thermal network strategy for electronic components

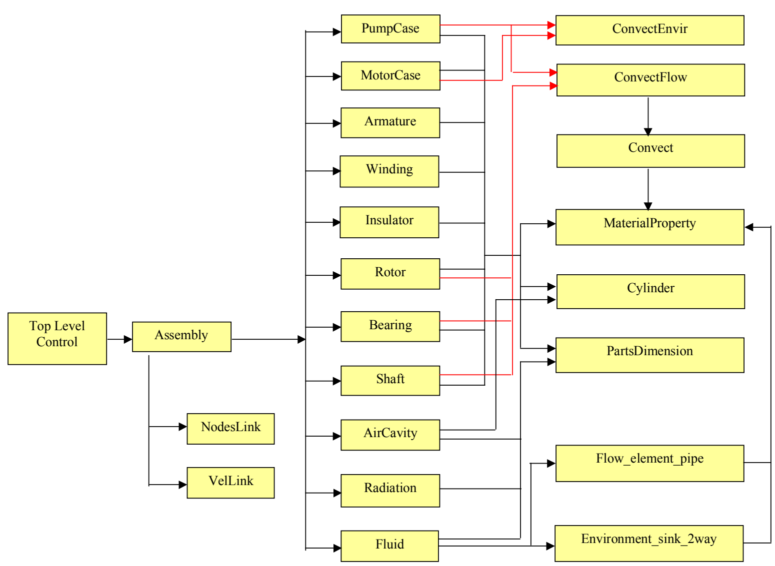


Figure 5. The flow chart for thermal network modeling of water pump motor

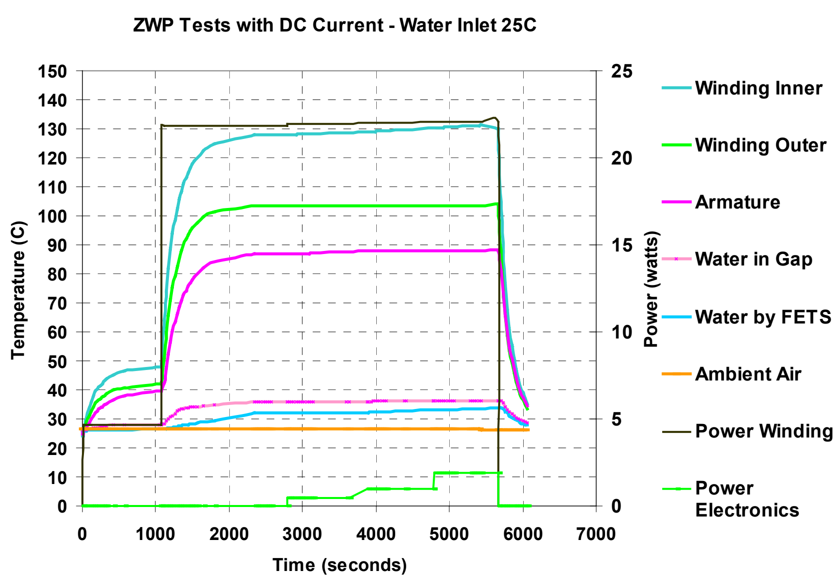
The model uses parameterized parts dimension and material property information, which is essential for geometry and material optimization during various design stages. The material properties are stored in a common library that can be used for all the motor models. The flow chart of the thermal networking for water pump motor is shown in Figure 5.

Time of simulation can be long for mixed signal simulation because the electronic models have very small time constants and the thermal models of the motors have such large time constants, meaning that a simulation in the range of 3600 seconds can take several hours to run. Therefore, an improved solution is adopted to speed up the simulation by sampling the electronics every few seconds to determine an "average" current, or rate of heat generation, and then applying this average to the thermal model until the next electronics sampling is performed. At which point, the component temperatures are updated and a new average current is calculated.

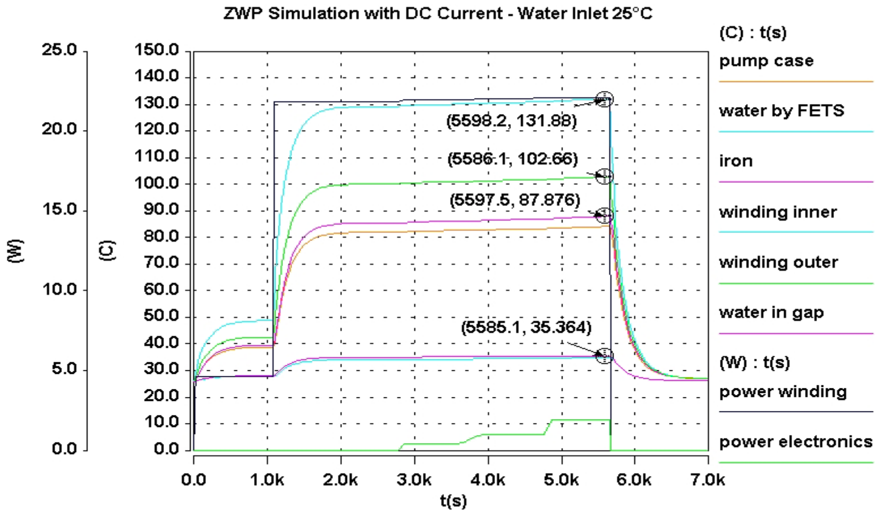
In order to enhance the usability of this thermal design toolkit and isolate the designers from most of the details of thermal modeling, a CAD-like GUI is under development where the geometry of the motor and a drawing of the network are presented showing temperatures, heat fluxes, and resistance values.

4 EXPERIMENTAL VERIFICATION

Several electronic controlled motors have been tested. The measured and simulated temperature profiles at certain locations as well as winding and electronic power loss of water pump motor are shown in Figure 6. During the experiments, a DC current in a winding is used to represent the winding power loss. Further testing in real working condition will be performed in the future. The ambient temperature and coolant inlet temperature is about 25°C. Good agreement is obtained and the corresponding steady state temperatures are listed in Table 1.



(a)



(b)

Figure 6. Motor experiments and simulation – water pump motor

Table 1. Comparison between testing data and simulation results.

	Stage 1 (at 1079 seconds)		**Stage 2 (at 5659 seconds)**	
	testing temp, °C	simulated temp, °C	testing temp, °C	simulated temp, °C
winding inner	48.00	48.76	130.00	131.88
winding outer	42.00	42.61	104.00	102.66
armature	39.60	39.50	88.20	87.88
water in gap	28.00	28.07	36.30	35.36
water by FETS	26.50	27.81	33.80	35.16

As expected, parameter tuning needs to be performed for the models, especially for the flow network as well as some contact surfaces, where accurate thermal resistance is difficult to obtain. However, once the experimental correlation has been performed, the model can be easily used for motor prototype design and geometry and material optimization.

5 CONCLUSIONS

Analytical-numerical hybrid, electronic-thermal coupled models for various electronic controlled motors have been presented in this study. The finite volume control block is created as a basic thermal component for heat conduction and flow network modeling is used to handle heat convection over fluid flow. Combined with other thermal components, a hierarchy of thermal network is established to simulate the thermal behaviors at the system level. A special timing scheme has been adopted due to the large difference of time step size between electronic models and thermal models. A wrapping template for electronic component has been implemented, enables the circuits designers to place electronic components in various locations and the thermal templates will handle the thermal issues. All the models are implemented as Saber templates using MAST scripting language (SaberDesigner 1999). A CAD-like GUI is being implemented using Tk/TCL scripting language. Good temperature prediction has been obtained for both steady state and transient simulations.

The thermal modeling tools and methodology can be used not only for certain type of motors, but also for other electronic-thermal coupled heat transfer simulation, such as electrical power devices, automobiles, and semiconductor systems.

6 ACKNOWLEDGEMENTS

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