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System thermal analysis for mobile phone

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Abstract

Thermal management is an important issue for mobile phone due to its small space and high power consuming density. On the basis of system experiment and numerical simulation, a thermal resistance network is established to analyze the whole mobile phone system in this paper. Our analysis shows that the maximum permission of power consumption is limited by the small surface area of mobile phone; and the surface temperature must be considered except the temperature of chips. Emphasis for thermal enhancement should be put on balance of cooling paths, for example, add material with high thermal conductivity between chip and battery, and make best use of the periphery surface area. Transient cooling method like phase change material can be considered also. In addition, this paper introduces some skills about how to calculate spreading thermal resistance for anisotropic and laminated heat sink.

Keywords: Mobile phone; Thermal resistance network; Spreading resistance; Thermal management

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1. Introduction

Mobile phone has become necessities for everyday life and attracted much attention due to its great market value. Manufacturers are integrating mobile phone with more and more functionalities while making it smaller and smaller. High consuming power and compact structure combine together and a great challenge comes for thermal management engineers.

Mobile phone is unique in thermal characteristics because it has not only high power density but also limited freedom for thermal enhancement. There is a vivid description, "A kind of device without heat sink". This means it is rather difficult to add heat sink and fan because both need space. Therefore, much emphasis is put on system analysis and design, including system numerical simulation and system experiment [1,2]. As it is known, thermal resistance network is a powerful tool for system analysis; it is a kind of thermal map in finding out the most effective solution to reduce the overall system thermal resistance. However, it is not easy to establish a thermal resistance network for mobile phone because of its complex cooling paths and complex structures. Another obstacle is spreading thermal resistance. Although many studies have been carried out about spreading thermal resistance [3–5], thermal management engineers often find it difficult to calculate because practical situations are usually different from the ideal geometry or the boundary hypothesis of the system. For the mobile phone analysis presented in this paper, there exist not only anisotropic materials but also laminated heat sink structures, both of which need special dealing when spreading thermal resistances are calculated.

In this paper, both system experiment and numerical simulation are carried out to observe the response of mobile phone to one heat source. Then spreading thermal resistances are calculated and a thermal resistance network is established. Analysis according to the thermal resistance network shows that the maximum permission of consuming power is constricted by the easily overheated small surface area; thermal enhancement should aim at a balanced thermal resistance network.

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Nomenclature

C	constant
H	convection coefficient (W/(m^2 °C))
h_{NC}	natural convection coefficient (W/(m^2 °C))
h_R	equivalent convection coefficient of radiation (W/(m^2 °C))
L	characteristic length (m)
Power	power consumption (W)
R	thermal resistance (°C/W)
T	temperature (°C)
ε	emissivity

Subscripts

air	ambient air
battery	battery of mobile phone
bottom	bottom case of mobile phone
convec	convection
heater	heater
keyboard	keyboard of mobile phone
material	solid material
pcb	PCB of mobile phone
s	surface
spread	spreading resistance

Superscripts

lower	the lower part of mobile phone, including bottom case and battery
n	through the thickness
system	the whole mobile phone system
upper	the upper part of mobile phone, including PCB and keyboard

2. Experiment and numerical simulation

Typically, the internal structure of mobile phone is laminated, in other words, mobile phone is composed of several layers: keyboard, PCB, chips, bottom case and battery. To simplify, the front case and keypad are considered as one layer, keyboard. Chips, which generate heat, are mounted on the PCB (printed circuit board). The bottom case acts as not only an enclosure wall but also a holder for the battery. Fig. 1 gives the schematic diagram of the mobile phone for our analysis purpose. Some mobile phones on the market may have different structures, for example, some have another layer: shield. Notwithstanding this, the five-layer mobile phone analyzed in this paper is typical; and the system analysis method used in this paper is referential for mobile phones with different structure.

2.1. Experiment setup

A simple experiment has been carried out to observe the mobile phone response to one heat source. Shown in Fig. 2 is the experiment apparatus. The mobile phone used in this experiment is Samsung SPH E2500. A commercial resistor (CCR-500-1, 10Ω, Component General, Inc.) is inserted into the mobile phone to function as a heat source when it is powered on. The heater is attached onto the biggest chip through interfacial thermal material. T type thermal couples with uncertainty of 0.5 °C are positioned to measure the temperature at interested points. The measurement points are shown in Fig. 3. The other things remain as if the mobile phone is still working.

Data acquisition Unit (Agilent 34970A) with high speed multiplexer module (Agilent 34901A) is used to get data from thermal couples. DC Power supplier (HP 6674A) provides constant DC power to the resistor. Both data acquisition unit and power supplier are connected to computer through GBIB-USB-B connector (National Instrument); and both are controlled by graphical interface program (Labview 6.1, National Instrument).

The mobile phone is left in the air. Temperature of the air varies little due to the air conditioning system for the laboratory building. Provide the resistor with a constant DC power; then the Labview program will record the necessary data every 1 s until a steady state is reached. Then

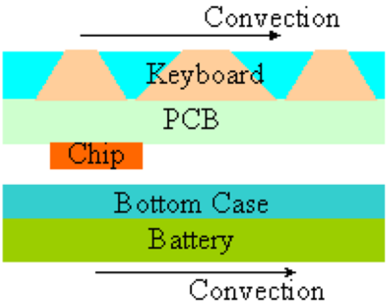

Fig. 1. Structure of mobile phone.

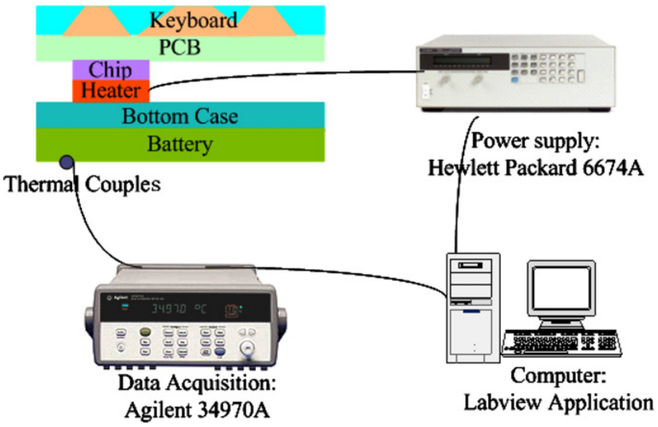

Fig. 2. Experiment setup.

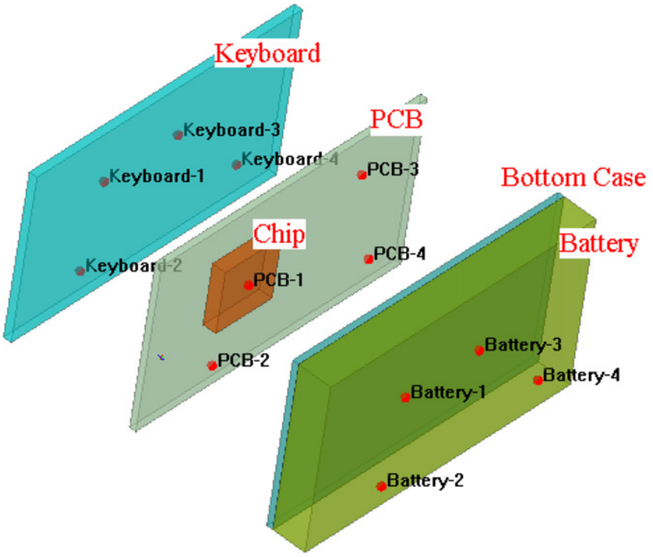

Fig. 3. Measurement points.

repeat the above procedure for a different value of power consumption, which ranges from 0.5 to 2.2 W in this paper.

2.2. Experiment results

Shown in Fig. 4 is the transient temperature responding to 1.5 W power consumption. The temperatures increase rapidly in the first 10 min after the power is turned on. Twenty minutes later, the temperatures change very little. One hour later, the system becomes almost completely steady. Then the last group of data is used in the following thermal analysis of steady state.

As shown by Fig. 5, the excess temperature over the ambient air is approximately proportional to the power consumption of the heater. This characteristic makes it easy to analyze the whole mobile phone system. Actually, mobile phone is held in an almost sealed enclosure. The air gap in the enclosure is so small that the air flow inside the mobile phone is negligible. In addition, the internal case walls are usually low emissive and the internal radiation can be ignored. Therefore, the heat transfer process inside the mobile phone can be modeled as conduction; Hasheme and Langari [1] claimed this kind of conduction model also. According to this model, the excess temperature should respond linearly to the power consumption of the heater, just as demonstrated by the experiment.

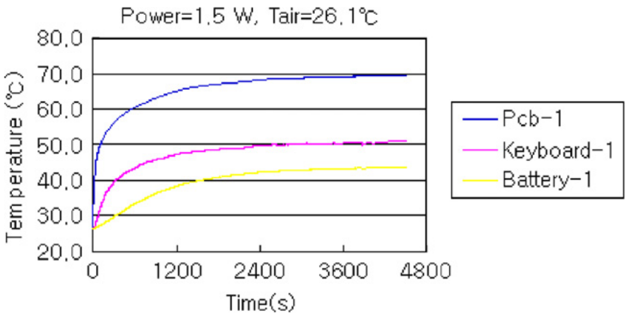

Fig. 4. Transient temperature.

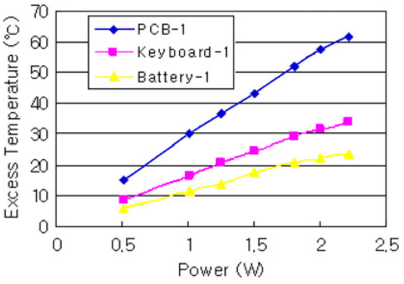

Fig. 5. Excess temperature responding to one heat source.

2.3. Hypothesis for the following analysis

The system analysis for mobile phone is based on the hypothesis of one heat source in this paper. Actually, there are more than one heat source in the mobile phone. Every chip on the PCB consumes certain amount of power and generates certain amount of heat. Even the battery will also give out some heat. Fortunately, the heat transfer process inside mobile phone is conduction; and the excess temperature responds linearly to the power consumption of the heater. Therefore, we can analyze the whole mobile phone system by observing the system response to one heat source. As a matter of fact, the highest power dissipating component in the mobile phone is Power Amplifier which consumes more than 50% power of the whole mobile phone. And this verifies our analysis with one heat source partially.

Another hypothesis is about geometry. All rounded edges and corners are simplified to be square in the following analysis. This simplification has some effect on the localized parameters at edges and corners. But there is almost no influence on the parameters in the central area and the overall solution.

In addition, the heater and the chip (which the heater is attached onto) are regarded as one block. This is because the thermal conductivity of the chip (silicon) is much higher than other components and the thermal resistance through the chip is negligible.

2.4. Numerical simulation

Thermal conductivities must be determined before numerical simulation. Thermal conductivity of pure material can be used as the in-plane thermal conductivity for every component layer. But the through-thickness thermal conductivity includes the effect of contact resistance. In addition, some components, like PCB, are anisotropic themselves. So it is difficult to get the through-thickness thermal conductivity. Therefore, through-thickness thermal conductivities are adjusted during numerical simulation so that temperature profile is consistent with experiment results. In this way, thermal conductivities are made certain.

2.4.1. Numerical simulation model

Numerical simulation is performed by using commercial software Ansys 8.0, on a three-dimension steady conduction model. The element adopted by the simulation is SOLID 90, which has 20 nodes with a single degree of freedom, temperature. The physical dimensions and the thermal conductivities assigned to each layer are shown in Table 1. The mesh representation is shown in Fig. 6.

Table 1
Input for numerical simulation

	Keyboard	PCB	Chip	Bottom case	Battery
In-plane thermal conductivity (W/(m °C))	3	9	150	0.1	8
Through-thickness thermal conductivity (W/(m °C))	0.07	0.3	150	0.1	0.5
Length (mm)	71.7	71.7	15.2	71.7	71.7
Width (mm)	41.2	41.2	15.2	41.2	41.2
Height (mm)	1.9	1.5	3.2	1.5	8.1

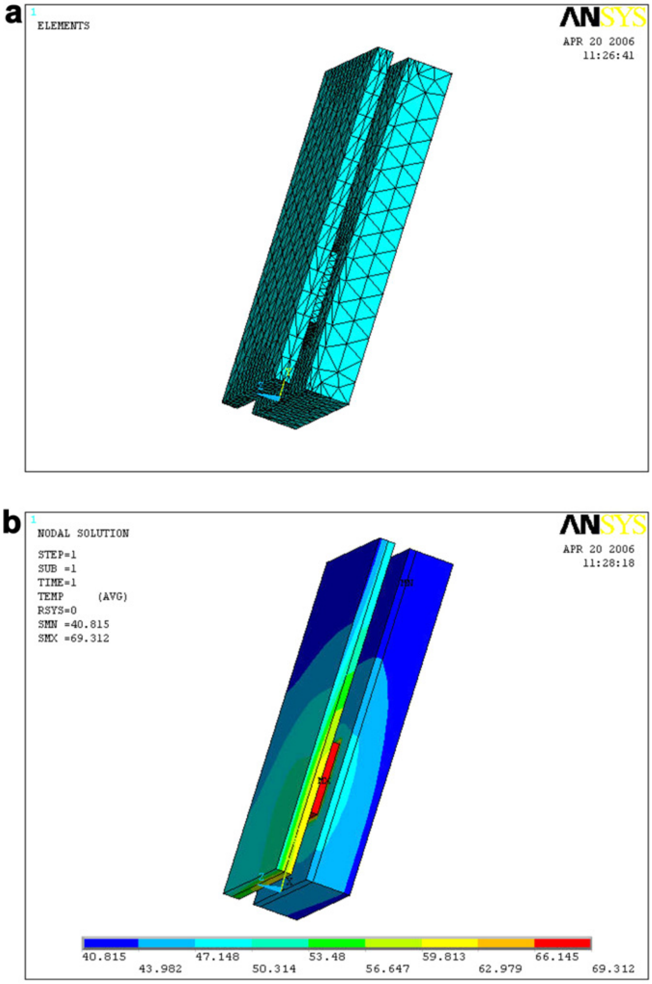

Fig. 6. Numerical simulation: (a) element representation and (b) results for 1.5 W power consumption.

Table 2
Temperature profile, Power = 1.5 W, $T_{air} = 26.1$ °C

Layer	Temperature on every point (°C)			
	1	2	3	4
PCB-experiment	69.4	52.5	47.6	45.9
PCB-simulation	69.3	54.4	49.9	47.5
PCB-comparison	0.1%	3.6%	4.8%	3.5%
Keyboard-experiment	50.8	48.4	47.6	43.6
Keyboard-simulation	50.4	47.2	46.0	41.9
Keyboard-comparison	0.8%	2.3%	3.4%	3.9%
Battery-experiment	43.6	43.6	43.8	41.7
Battery-simulation	42.9	42.7	41.8	40.9
Battery-comparison	1.4%	2.1%	4.6%	1.9%

2.4.2. Boundary conditions

The chip and heater block is assigned volume heat generation loads. The surfaces are assigned constant convection coefficient. The constant convection coefficient h includes both natural convection effect h_{NC} and radiation effect h_R. They are calculated according to Eqs. (1)–(3).

$$h_{NC} = C^*((T_s - T_a)/L)^{0.25} \tag{1}$$

$$h_R = 5.67 \times 10^{-8} * \varepsilon * \left((T_s + 273)^2 + (T_{air} + 273)^2\right)((T_s + 273) + (T_{air} + 273)) \tag{2}$$

$$h = h_{NC} + h_R \tag{3}$$

where C is constant, which depends upon the orientation of surface [6]; L is the characteristic length, m; ε is the emissivity of surface material, $\varepsilon = 0.94$ for PVC material; T_s is the average surface temperature, °C; T_{air} is the temperature of air, °C.

2.4.3. Numerical simulation results

The numerical simulation result for 1.5 W power consumption is shown in Fig. 6. Comparison between experiment and numerical simulation is listed in Table 2. The result is acceptable even though disagreement exists. The disagreement exists partially because size of the components is regularized and partially because some parameters, such as convection coefficient, are considered as constants in numerical simulation.

3. Thermal resistance network

Cooling paths must be analyzed before establishing the thermal resistance network. According to the conduction cooling model stated before, there are two heat transfer paths for the mobile phone system. For one way, heat generated in the chip is first conducted into PCB, then is transported into the keyboard by conduction, and finally is removed into the ambient air by natural convection. The other way is through bottom case and battery. Heat first passes through bottom case and battery by conduction, and then enters into the environmental air by natural convection. Accordingly thermal resistance network should have two branches. For each branch, both spreading resistance and through-thickness resistance must be calculated.

Spreading thermal resistance exists in the base-plate when a heat source of smaller footprint area is mounted on a heat sink with a larger base-plate area. Seri Lee [3,4] has developed a useful and simple method to calculate spreading resistance for general boundary conditions. The problem is that heat sinks in this paper are made up of several layers, and materials for every layer are anisotropic. Therefore, special simplification is necessary before we calculate spreading resistance by using Seri Lee's formula.

3.1. Spreading resistance through PCB and keyboard

The in-plane thermal conductivity of PCB is much greater than the thermal conductivity of keyboard. Temperature is spread mainly through PCB and the spreading effect through the keyboard is negligible. And the thermal resistance through the keyboard can be regarded as part of the overall thermal resistance of heat sink R_0 in trying to use the Seri Lee formula. The schematic diagram is shown in Fig. 7, where $R_{\text{spread}}^{\text{upper}}$ is the spreading resistance through PCB; R_{pcb}^{n} is the resistance through thickness of PCB; R_{keyboard}^{n} is the resistance through thickness of keyboard; R_{convec} is the convection resistance across surface of keyboard.

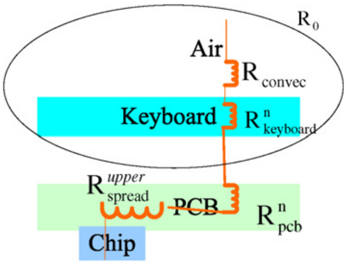

Fig. 7. Resistance through PCB and keyboard.

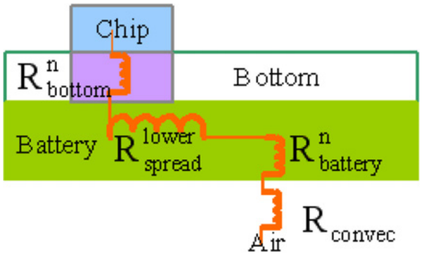

Fig. 8. Resistance through bottom and battery.

When calculating $R_{\text{spread}}^{\text{upper}}$, the in-plane thermal conductivity of PCB is used. This is because the in-plane thermal conductivity of PCB is much bigger than the through-thickness thermal conductivity of PCB; and the spreading effect occurs mainly in the plane direction [5]. However, the amount of heat penetrating through PCB is determined by R_{pcb}^{n}, which can be calculated by using the through-thickness thermal conductivity.

3.2. Spreading resistance through bottom case and battery

The thermal conductivity of battery is much greater than the thermal conductivity of bottom case. Temperature is spread mainly through the battery. The spreading effect through the bottom case is negligible. So the bottom case can be simplified as a block with the same footprint area as the chip, as shown by Fig. 8, where R_{bottom}^{n} is the resistance through virtual bottom; $R_{\text{spread}}^{\text{lower}}$ is the spreading resistance through battery; R_{battery}^{n} is the resistance through thickness of battery; R_{convec} is the convection resistance across surface of battery.

3.3. Thermal resistance network

Thermal resistance network for the mobile phone system is shown in Fig. 9. As we see, the thermal resistance network has two branches which correspond to the two cooling paths. According to the thermal resistance network, the temperature of heater T_{heater}, the area-averaged temperature of keyboard T_{keyboard}, and the area-averaged temperature of battery T_{battery} can be calculated in the following way.

$$T_{\text{heater}} = R^{\text{system}}\text{Power} + T_{\text{air}} \tag{4}$$

$$T_{\text{keyboard}} = \frac{R_{\text{convec}}R^{\text{lower}}}{R^{\text{upper}} + R^{\text{lower}}}\text{Power} + T_{\text{air}} \tag{5}$$

$$T_{\text{battery}} = \frac{R_{\text{convec}}R^{\text{upper}}}{R^{\text{upper}} + R^{\text{lower}}}\text{Power} + T_{\text{air}} \tag{6}$$

Table 3 gives comparison between the experiment results and the calculation results by using Eqs. (4)–(6). Where, the experiment temperature, T_{keyboard} and T_{battery} are arithmetic-averaged temperature for several measured points.

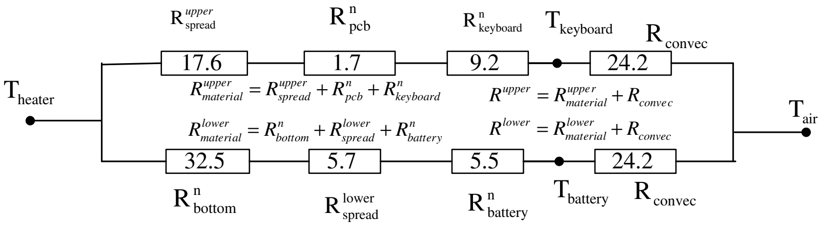

Fig. 9. Thermal resistance network for mobile phone system.

Table 3
Comparison between experiment and calculation through resistance network

Power (W)		0.509	1.011	1.250	1.500	1.800	2.000	2.217
T_{air} (°C)		26.9	26.6	25.8	26.1	26.9	26.1	26.9
T_{heater} (°C)	Experiment	42.3	56.6	62.3	69.4	79.0	83.5	88.7
	Calculation	41.7	56.2	62.8	70.5	80.2	85.3	92.0
	Comparison	1.4%	0.7%	0.8%	1.5%	1.5%	2.2%	3.8%
T_{keyboard} (°C)	Experiment	34.6	41.0	44.1	47.6	52.4	53.5	56.3
	Calculation	33.7	40.2	42.8	46.5	51.4	53.3	56.8
	Comparison	2.5%	1.8%	2.8%	2.3%	2.0%	0.4%	0.9%
T_{battery} (°C)	Experiment	32.9	38.0	39.6	43.2	47.2	47.9	50.1
	Calculation	32.2	37.2	39.1	42.0	46.0	47.3	50.2
	Comparison	2.0%	2.2%	1.3%	2.7%	2.5%	1.3%	0.3%

4. System analysis and discussion

4.1. Ideal thermal resistance network

Given the convection resistances in the two branches are almost equal, heat dissipated through keyboard and heat dissipated through battery had better be equal. Otherwise, the keyboard may have been overheated while the battery temperature is still much lower than the maximum permission. Therefore, an ideal thermal resistance network must be balanced in two branches; to be further, material resistances $R^{\text{upper}}_{\text{material}}$ and $R^{\text{lower}}_{\text{material}}$ should be equal with each other.

As for each branch, there are two limitations for the maximum permission of consuming power. First, like any other electronic devices, the working temperature of the chip cannot be too high. The unusual thing for mobile phone lies in the second limitation. As it is known, surface of mobile phone must contact with human body. If the surface temperature of the mobile phone is too high, the user will feel uncomfortable. So the surface temperature is also a limitation for the maximum permission of consuming power. According to the thermal resistance network in Fig. 9, there are Eqs. (7) and (8).

$$\frac{R^{\text{upper}}_{\text{material}}}{R_{\text{convec}}} = \frac{T_{\text{heater}} - T_{\text{keyboard}}}{T_{\text{keyboard}} - T_{\text{air}}} \tag{7}$$

$$\frac{R^{\text{lower}}_{\text{material}}}{R_{\text{convec}}} = \frac{T_{\text{heater}} - T_{\text{battery}}}{T_{\text{battery}} - T_{\text{air}}} \tag{8}$$

If the chip and the surface reach the maximum permission of temperature at the same time, an ideal proportion between material resistance and convection resistance can be got. For example, suppose the maximum temperature permission for heater and surface is 80 °C and 40 °C respectively, then there is Eq. (9).

$$\frac{R^{\text{upper}}_{\text{material}}}{R_{\text{convec}}} = \frac{R^{\text{lower}}_{\text{material}}}{R_{\text{convec}}} = \frac{80-40}{40-25} \approx \frac{73\%}{27\%} \tag{9}$$

To summarize, an ideal thermal resistance network should be a balanced one. Just as shown by Fig. 10, the two branches are balanced; and the material resistance and the convection resistance are balanced also. Inspect Fig. 9, the real thermal resistance network is far from an ideal one. R^{lower} is much bigger than R^{upper}; in other words, $R^{\text{lower}}_{\text{material}}$ is much bigger than $R^{\text{upper}}_{\text{material}}$; to be further, R^{n}_{bottom} is really a big thermal resistance which needs to reduce for thermal enhancement. At the same time, the convection resistance takes too high a percentage; in other words, the ratio between material resistance and convection resistance is not ideal also.

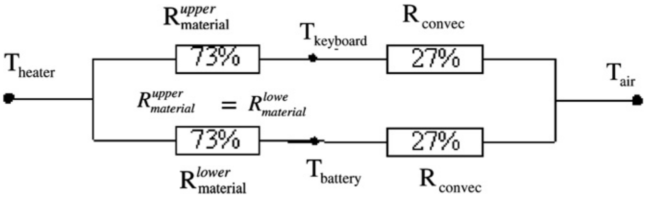

Fig. 10. Ideal thermal resistance network.

4.2. Thermal enhancement

Thermal design usually includes two interactive problems: decreasing the temperature of the overheated components and improving the power permission. For the first, if it is chip that overheats, reducing any of the resistances is beneficial. Of course some is more effective; and the target should aim at the biggest resistance and the bigger branch. But for our system, the surface is more easily overheated, especially the keyboard, just as demonstrated by Tables 2 and 3. This is because of the high proportion of the convection resistance and the imbalance of the two branches. To solve this problem, the first answer is to reduce R^{n}_{bottom}. For example, adding material with high thermal conductivity, as described by Ref. [7].

The second way is of course to reduce the convection resistance. However this is not as easy as the first one because both methods, increasing surface area and changing into forced convection, are restricted by the small space of the mobile phone system. Therefore making best use of the existing surface area is a good policy; periphery area and display part of the folded-type mobile phone may be a good choice.

All the above balancing jobs can help to improve the permission for power consumption, but we have to pay attention to the surface area constriction. As it is known, all the heat must enter into the ambient air through the surface natural convection under steady state. Suppose the surface temperature is even, the max power which can be dissipated through natural convection is definite when the surface temperature reaches its limit. Therefore new cooling methods, for example, change the structure of thermal resistance network, are necessary.

In addition, the above analysis is based on an assumption, namely, the mobile phone system reaches a steady state. For mobile phone which is operated intermittently, the transient process may be considered when solving the cooling problem. For example, Tan and Tso [8] used phase change material to prolong the transient process in the cooling for mobile electronic devices.

5. Conclusion

System experiment and numerical simulation show that the excess temperature is approximately proportional to the power consumption and conduction is the predominant heat transfer way inside the mobile phone. On the basis of conduction model and one heat source assumption, spreading resistances are calculated and a thermal resistance network for the whole mobile phone system is established.

System analysis based on thermal resistance network shows that the surface is easily overheated and the surface temperature should be another consideration except the temperature of chip. The maximum permission of power consumption is constricted by the small surface area of mobile phone under natural convection. Thermal enhancement should aim at a balanced thermal resistance network. Periphery area and display part of the folded-type mobile phone can be used to increase the cooling surface area. Materials with high thermal conductivity can be added between the chip and the bottom case to enhance the thermal management. In addition, transient process can be considered for mobile phone which is operated intermittently, for example, using phase change materials to prolong the transient process.

Indeed, the analysis in this paper is about one type of mobile phone model and the thermal resistance network is not an accurate analysis because of the simplifications and hypotheses. But this kind of system analysis is necessary and beneficial at the beginning and can help find directions for the advanced study. In addition, some simplification skills, such as the calculation method of spreading resistance for layered heat sink, are useful for other circumstances also.

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