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FAST THERMAL EXPLORATION IN THE PRELIMINARY DESIGN OF ELECTRONIC PRODUCTS

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ABSTRACT

This paper presents the verification of a model that supports the fast thermal exploration of electronic product concepts. The aim of the model is to provide a first order exploration of passive versus active cooling and provides design engineers an instrument for communicating with electronic engineers. The model can be used to evaluate an electronic product concept based on both power dissipation and the surface area of the minimum enclosing box. The present study shows that the model is understandable and easy-to-use and can practically be used for first order exploration of thermal design of electronic products. The model gives an indication whether or not the existing concept demands more detailed exploration of the temperature development in a device. The model can also be used by the designer to discuss if it is theoretically possible to naturally cool the product concept dependent on the ergonomic temperature criteria of the encasing.

Keywords: Thermal design, rule-of-thumb, passive cooling, active cooling

1 INTRODUCTION

Designers must be able to do quick estimations during the very early stages of product design. During the conceptual stage of product design a number of different comparisons must be made for the relevant criteria for several possible product proposals. Maximum allowed temperature is one of the criteria that are of special importance in the design of electronic products. From an ergonomics point of view there is a limit temperature of the encasing and, in the case of forced convection, a limit temperature of the air flowing out of the product. From a reliability point of view there is a maximum allowed temperature of the electronic components which are usually based on manufacturers' specifications. The continuing trends in electronics, such as miniaturization, ubiquitous electronics and telecommunications increase the importance of thermal management and relating reliability issues.

There are several focuses of thermal management in science and practice found in literature. Among the different areas in thermal management research three main areas can be defined.

The first area of research focuses on the generation of heat and general heat transfer theory. The focus is mainly on modelling of natural convection and forced convection in electronic enclosures [1-4], structural optimization and integration of components with regard to PCB layout [5-8].

A second area is analysis and simulation in which the focus is on studies of flow network models and resistor network theory [9-10], experimental analysis, numerical analysis such as computational fluid dynamics (CFD) and finite element method (FEM) [11-12] and reliability issues [13].

Finally there is the focus on thermal management techniques [14] such as heat sinks, fans, heat pipes, phase-change cooling and software thermal management algorithms.

Current evaluation methods such as resistor network theory, FEM, and CFD are mostly appropriate for embodiment and detail design and therefore do not practically support the the fast exploration of components and basic lay-out options. This is the result of some general problems. First, to our best knowledge there are no simple thermal models that design engineers can use in conceptual design to analyse and optimise concepts. Second, the models that do exist are mostly using steady-state heat transfer mostly for larger electronic encasings. Furthermore in thermal analysis in general there is little attention to conceptual design. Finally, the approximation of heat transfer coefficients is difficult in design areas that lack the availability of CFD software. Considering temperature analysis in the conceptualisation stage of electronic product design requires another approach.

The models by Ishizuka [2-3] and Yazawa [10] are closely related to the model presented here which to some extent continues the work that they have done. In our paper however, the models are extended with own empirical studies and a description of a method for practical application. The usability and usefulness of the method for practical application is verified by means of experiments and interviews.

We propose to develop a model that can be used as a rule-of-thumb for fast thermal exploration of electronic products. The aim of the model is twofold. The primary aim is to provide a model for first order exploration of the choice between passive or active cooling. The secondary aim is to give design engineers a means for communicating with the electronics engineer. We expect that by using the proposed model, a thermally acceptable design of electric appliances can be reached relatively fast and wrong design decisions can be avoided.

In section 2 the method that has been used to develop the model is explained. Section 3 presents the results of the measurements that have been done. In section 4 the model is validated by means of dimensional analysis. A discussion of the results is given in section 5. The paper follows with describing the use of the result in section 6 where a method to apply the model during concept design is explained. The following section discusses verification of the method by experiments and discussion with people from the field. The final section gives conclusions and recommendations based on the presented research.

2 MODEL

In this paper the model will be defined using two aspects. First, the theoretical cooling limits for several temperature differences are derived resulting in the combined convective and radiative heat transfer coefficient from an isothermal surface to the ambient environment. Second, a comparison of measurements of actual products against the theoretical values is used to define the boundary and transition area between passive and active cooling.

2.1 Model definition

The theoretical cooling limit of electronic products has been approximated with the aim of defining the boundary area between passive cooling and active cooling of an electronic product. The approximations are for heat transfer between an isothermal surface temperature T_e and the ambient temperature T_a. A characteristic dimension of a vertical plate L of 0,1 m and thermal conductivity of air k are used to calculate the heat transfer coefficient of convection h_c and the heat transfer coefficient of radiation h_r at temperature differences T_e-T_a of 5K, 15K and 25K.

$$h_c = \frac{k \bullet Nu_L}{L} [W/m^2 \bullet K];\ Nu_L = 0{,}54 Ra_L^{\ 0{,}25} \tag{1}$$

$$h_r = \varepsilon \sigma F_{1,2} 4 T_{\_}^{\ 3} [W/m^2 \bullet K] \tag{2}$$

The heat transfer coefficients have been approximated by means of standard heat transfer theory. The point of departure for the calculation of the heat transfer coefficients of radiation and of convection is a vertical plate with an isothermal temperature distribution across the surface. For the approximation of h_c the hilpert correlation which is shown in Eq. 1 [15] has been used to approximate the nusselt number Nu_L. The heat transfer coefficient of radiation is approximated by using the average temperature $T\_ = (T_a - T_e)/2$, emissivity ε, Stefan-Boltzmann constant σ and radiation shape factor $F_{1,2}$ and is given in Eq. 2 [16]. Values and properties can be found in [17]. It is supposed that the conductive heat transfer coefficient from the encasing exterior to the environment is negligible. The resulting total heat transfer coefficient h_{tot} is then calculated by summation of h_c and h_r.

Table 1 shows the results. The average temperature $T\_$ that is used in calculation of the radiative heat transfer coefficient is the mean of T_a and T_e.

Table 1. Heat transfer data.

	T_a-T_e = 5K	T_a-T_e = 15K	T_a-T_e = 25K
h_r [W/m^2•K]	6,03	6,34	6,66
h_c [W/m^2•K]	3,72	4,85	5,47
h_{tot} [W/m^2•K]	9,75	11,19	12,13

2.2 Experimental measurements

In order to test the model for the passive cooling limit of electronic products, the power dissipation *Q* and area of the minimum enclosed box *A* of 66 electronic products has been measured. The sample of this test contains 13 actively cooled products, 47 passively cooled products and 6 products containing a heating element. For the purpose of more insight, measurement of the steady state temperature of the hotspot T_h has been included in the measurements of a set of 21 products. The sample of this test contains 16 passively cooled products and 5 actively cooled products. Products with a heating element are rather specific because their function is explicitly to produce and to transfer heat (toasters, water cookers etc.).

From the measurements $T\_$ has been derived which is needed to calculate the heat transfer coefficients of radiation and convection. All temperatures are measured in steady-state situation. The surface area has been approximated by measuring the area of the minimum enclosing box *A* of the products. T-type thermocouples where attached on those locations where the hot spot was expected. Figure 1 shows three product examples.

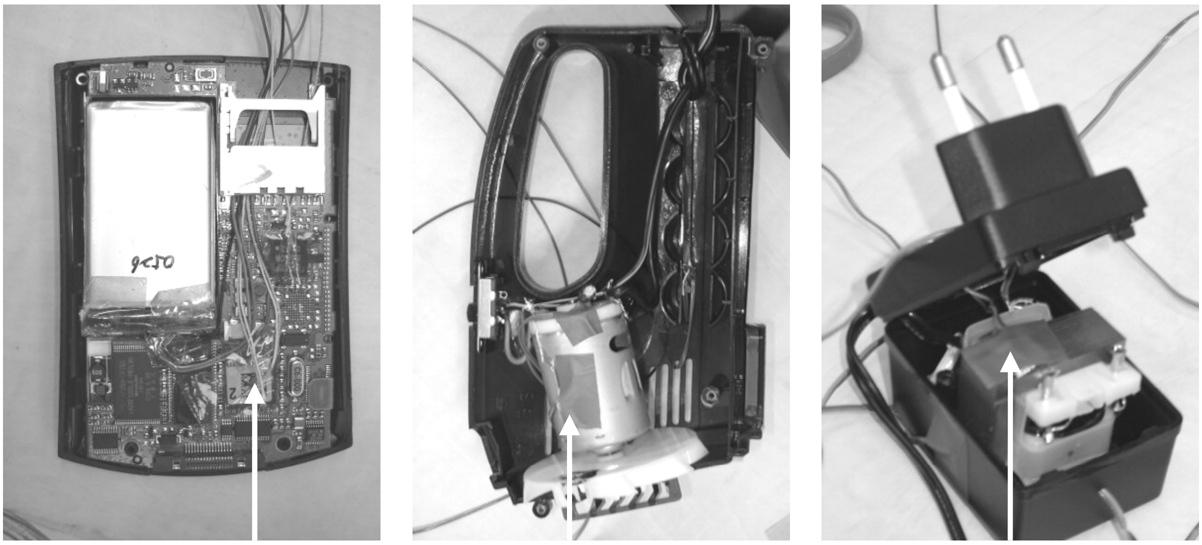


Figure 1. Thermocouples attached to the hotspot inside the encasing, measure T_h of a PDA, car vacuum cleaner and AC-DC adaptor

3 MEASUREMENT RESULTS

In order to compare the measurement results to the theoretical values, the measured products have been classified in three categories namely passively cooled products, actively cooled products and heating products. Passively cooled products release their heat mainly through the surface of their encasing, actively cooled products use forced air flow (a fan) for temperature control and the products that use heating as a function are designed to withstand high temperatures.

3.1 Power and area measurements

For a total of 66 products the surface area *A* and power dissipation *Q* has been measured. Figure 2 presents both the calculated heat transfer lines and positioning of the experimental results. Interpretation of experimental results shows a separation between passively and actively cooled products namely the line belonging to a 15K temperature difference. The line appears to be a clear boundary between the passively cooled and actively cooled products. In order to create a transitional area from passive to active the lines that represent a 5K and a 25K temperature difference have been added.

The values of *A* varied between $8{,}0 \cdot 10^{-3}$ m^2 (portable radio) and 3,0 m^2 (washing machine). *Q* varied between $2{,}0 \cdot 10^{-2}$ W (portable radio) and $2{,}0 \cdot 10^{3}$ W (watercooker). Figure 2 shows that most products which dissipate less than 1 W of power are positioned below the 5K temperature line. Products that consume between 1 W and 10 W are predominantly positioned from around the 5K line up to the 15K line. The actively cooled products those that dissipate between 10 W and 100 W are more close to the 15K line than products that dissipate over 100 W.

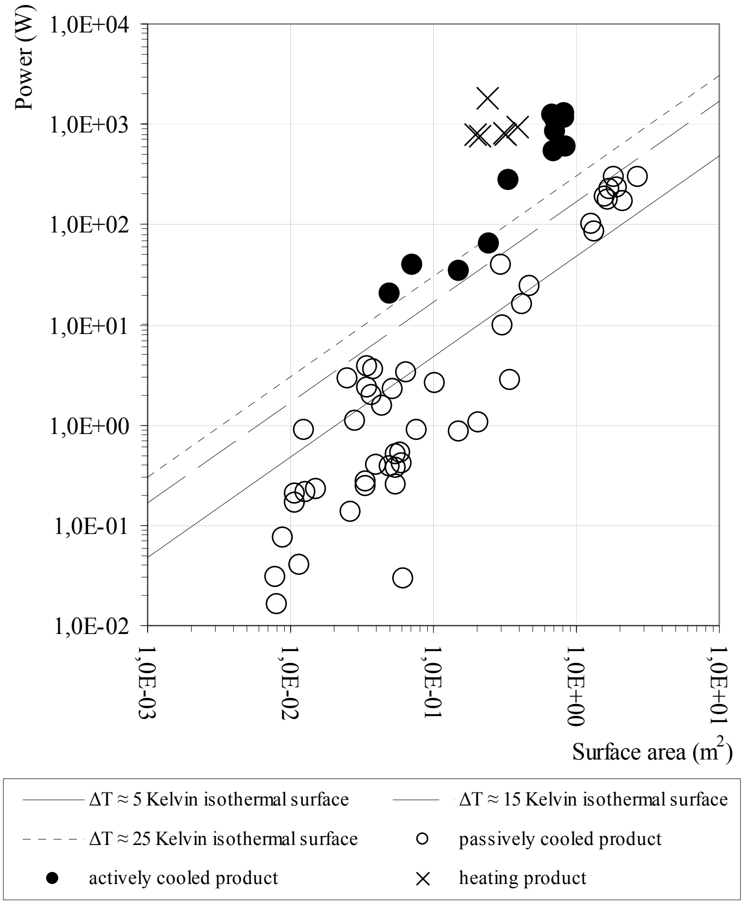


Figure 2. Existing products and theoretical cooling limits

3.2 Temperature measurements

For 21 products the temperature T_h of the hotspot (typically an electromotor, transistor or integrated circuit) was measured during steady-state temperature. Figure 3 shows the data of the measurements. Also the surface area of the product's minimum enclosing box and the power consumption is included and the ratio *Q/A* which is a measure for the area specific power of the product.

It seems that generally the temperature of the hotspot increases when the power consumption increases. In thermal design the critical temperature of most components lies above 353K (70°C) [18]. The present results suggest that for actively cooled products (Tyre Pump, Slide projector) the previously derived *Q/A* ratio of 300 is critical and for passively cooled products (airpump, CD player, lamp) a *Q/A* ratio of 50 is critical.

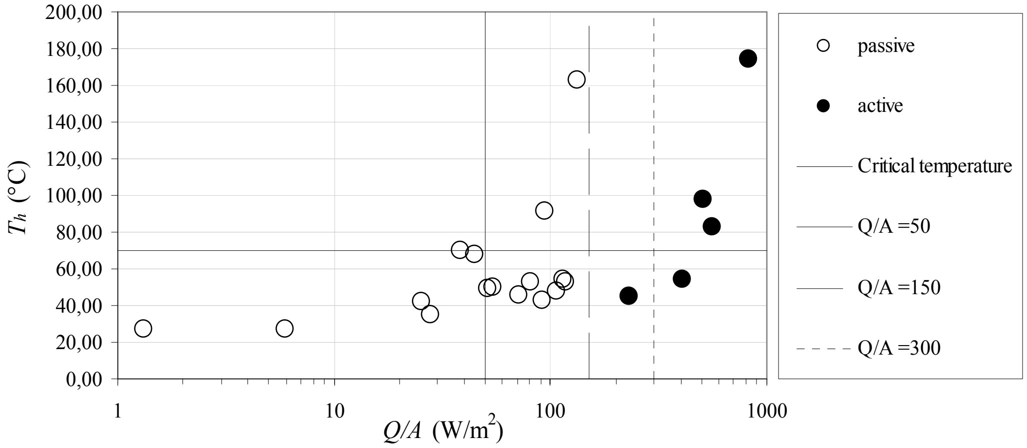


Figure 3. Temperature evaluation

4 VALIDATION

On the basis of dimensional analysis it will be shown that passively cooled products and actively cooled products show a significant different working area regarding surface temperature. The background of dimensional analysis theory states that the physical principle of a phenomenon can be described by the definition of dimensionless numbers, based on the parameters that influence the phenomenon [19]. The hypothesis is formulated by reducing the matrix equation of the parameters of the phenomenon and deducing the dimensionless numbers. With the aim of theoretically exploring the validity of the model the measurement results will be used for defining a theoretical hypothesis that defines the physical relations between Q, A, T_e, T_a and h_{tot}.

There are several variables that must be taken into account for the analysis to be exact: the overall heat-transfer coefficient (h_{tot}), the dissipated power (Q), the temperature difference between T_a and T_e (ΔT), the ambient temperature, (T_a) and the surface area of the minimum enclosed box (A). Because this project takes into account only the steady state situation the thermal capacity of the components of an electronic product can be left out of the analysis.

Table 2 and Table 3 show both the dimensional matrix and the reduced row echelon form (RREF) matrix. From the RREF matrix the dimensional numbers necessary to describe the phenomenon can be easily derived. From basic dimensional analysis theory we know that because there are two free variables that there are also two dimensionless numbers.

Table 2 dimensional analysis matrix

	A	Q	ΔT	T_a	h_{tot}
M	0	1	0	0	1
L	2	2	0	0	0
T	0	-3	0	0	-3
θ	0	0	1	1	-1

Table 3 RREF dimensional analysis matrix

1	0	0	0	-1	A
0	1	0	0	1	Q
0	0	1	1	-1	ΔT
0	0	0	-1	0	T_a
0	0	0	0	-1	h_{tot}

On the basis of the dimensional analysis we can now propose the dimensional hypothesis Eq. 3. In order to derive the constant C and the exponent a it is necessary to carry out a regression analysis on the measured data. The values needed in the dimensional analysis hypothesis can be derived from the logarithmic scatter plot of the two dimensional numbers and the relating function. All the data needed is available, namely Q, A, ΔT, T_a, the heat transfer coefficient h_{tot} was set at 11,2 W/m^{2}K which is the mean of the three heat transfer coefficients in Table 1. Eq. 4 and Eq. 5 show the results for passive and active cooling.

$$\left(\frac{\Delta T}{Ta}\right) = C \bullet \left(\frac{Q}{h_{tot} \bullet Ta \bullet A}\right)^a \tag{3}$$

$$\text{Passive: } C = 10^{-0,3901} = 0,41; a = 0,59 \tag{4}$$

$$\text{Active: } C = 10^{-0,0006} = 1,00; a = 1,73 \tag{5}$$

Figure 4 shows the analysis of the data. Two regions can clearly be defined which separate the passively cooled devices (area on the left) from the actively cooled devices (area on the right). From the rising regression lines of both scatter areas we can conclude that larger temperature differences ΔT are accepted in the design when the products have a higher power consumption. This account for both actively cooled and passively cooled products. Also the line ($\Delta T/T_a$) varies between -1 and -2,5 which means that (at an ambient temperature of 296K) the ΔT varies with between the following approximations: $10^{-2,5} \bullet 296 < \Delta T < 10^{-1} \bullet 296 \sim 1\text{K} < \Delta T < 30\text{K}$.

In addition we can see that two areas are separated by the line (*Q/h•A•ΔT*) of -1,5. This indicates that if the value of log (*Q/h•A•ΔT*) becomes greater than -1,5 the *ΔT* with regard to the surface temperature becomes over 50K. When this results in ergonomically unpleasant situations the designer can conclude that there is a must for active cooling (a fan) or increasing the surface area of convective cooling (a heatsink).

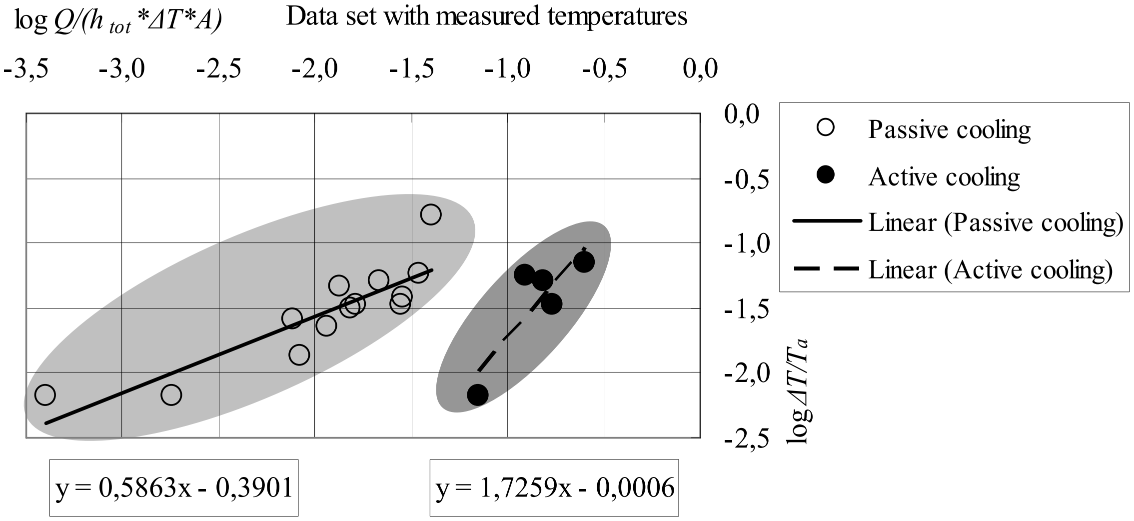


Figure 4 dimensional analysis results

5 DISCUSSION

One of the decisions in the development of thermally critical designs is whether or not it is necessary to use active cooling to prevent the encasing from reaching an unacceptable temperature. A first-order exploration of this issue has been supported by taking into account the maximum limit of passive cooling and comparing the results with measurements on actual products.

From the results we can derive that certain products such as the microwave oven, toaster and car vacuum cleaner can not be passively cooled through the encasing. The *ΔT*, would result in either too large surface areas or really high encasing temperatures (approximately 100 degrees Celsius). We know that in practice these products are either insulated from the user (toaster) or cooled by forced convection (microwave and vacuum cleaner).

On the basis of Figure 2 a transition area can be defined that the designer must be aware of. If *ΔT* is in between 5K and 25K there appears to be a transition between simple passive cooling and comprehensive active cooling. On the basis of Figure 3 and Figure 4 it is assumed that the designer must be careful with passive cooling in the range of 5K to 15K. Active cooling can be applied between 15K and 25K with confidence. Active cooling above the 25K line however requires a more extensive thermal study.

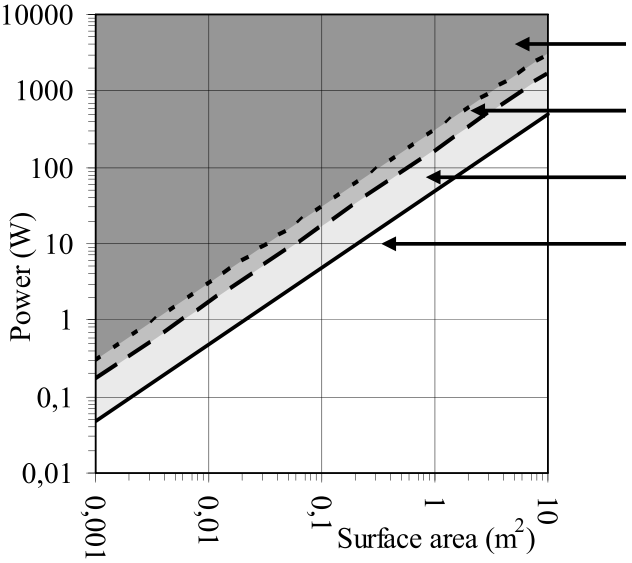
These guidelines are additionally quite obvious merely from an ergonomic perspective. Consumer products with such high surface temperatures can be an ergonomic hazard to the consumer if touched with bare hands (also dependent on the material properties of the encasing).

The heating products show up high in the graph in the forced convection area, representing a high area specific power and high surface temperature, which is typical for these types of products. These products do in fact have either a fan (microwave) or shut down at a certain temperature (watercooker) which explains why the area specific power of these products can be so high.

6 PRACTICAL USAGE OF THE MODEL

The model presented in Figure 5 gives the designer some rough guideline on whether passive cooling of the product is feasible by knowing only the approximate power consumption and the surface area of the minimum enclosing box. Depending on the type of product the probability that critical hotspot temperatures will occur in the design can now be roughly predicted.

Products in zone 1 (see Figure 5) have ΔT > 25K and appear to be actively cooled and have a high possibility of hotspots. In this case detailed thermal analysis is advised. In zone 2 (25K > ΔT > 15K) the products are actively cooled and relative secure regarding hotspots. Products in zone 3 (15K > ΔT > 5K) appear to be passively cooled and have a high chance of hotspots, here also detailed thermal analysis is advised. In zone 4 (25K > ΔT > 15K) the products are passively cooled and relative secure regarding hotspots.



Zone 1: *Q/A* > 300, Active cooling, detailed thermal analysis is essential
Zone 2: 300 < *Q/A* < 150 Active cooling, low thermal risk
Zone 3: 150 > *Q/A* > 50 Passive cooling, detailed thermal analysis is essential
Zone 4: *Q/A* < 50 The product can be passively cooled

Figure 5 model and practical application

The application of the model is twofold. Firstly, the model is to be used in the very early stages of design (conceptual phase) to gain some insight in whether or not it is necessary to use active cooling. The designer begins by defining the ratio *Q/A*. Then he or she follows with positioning of the design in the graph or comparing the results to the rule-of-thumb described above. The analysis ends with a decision on whether or not to use a fan in the design and an assessment of the need for detailed thermal analysis in subsequent design phases.

Secondly, the rule of thumb can be used as a means of communication between design engineers and electronic engineers. For practical purposes the temperature lines are not appropriate. A new measure is therefore proposed that is the ratio *Q/A*. If the ratio *Q/A* changes compared to previous designs by either an increase in power consumption or a reduction of product surface area. The designer and electronic engineer must again assess the product on the basis of the rule-of-thumb and estimate whether or not a change in design or a more extensive thermal analysis is required.

By examining the temperature lines the corresponding ratios of *Q/A* can be derived. For 5K the ratio *Q/A* ≈ 50, for 15K the ratio *Q/A* ≈ 150 and for 150K the ratio *Q/A* ≈ 300. The designer can get some insight whether detailed analysis of the temperatures within the product is necessary based on a simple rule-of-thumb. The following, however, does not apply for the development of heating products (e.g. toasters, watercooker etc.) and must take into account a different approach than presented here.

The model is applied as follows for a given design:

1. Estimate Q and A of your design
2. Determine in which of the zones in Figure 2 your design is positioned.
   2.1. If Q/A > 300 the design lays in zone 1 then active cooling, detailed thermal analysis is essential
   2.2. If 300 < Q/A < 150 the design lays in zone 2 then active cooling can be used with low thermal risk
   2.3. If 150 > Q/A > 50 the design lays in zone 3 then passive cooling is an option but detailed thermal analysis is essential
   2.4. If Q/A < 50 the design lays in zone 4 then the product can be passively cooled
3. Make decisions, set criteria and reuse the model when significant design changes in Q or in A occur.

7 VERIFICATION

In order to verify the method of practical application of the model a qualitative user research has been carried out. The aim is to obtain insight in the usability and the usefulness of the method. The research consists of two parts: 1) an experiment with 8 design students to discuss the usability of the method and 2) interviews professional designers to discuss the usefulness during the conceptual design phase.

5.1 Usability experiment

The present experiment aims at investigating the usability of the method. Concerning this the following research questions have been studied.

- Is the method properly understood and if not which mistakes occur?
- Do the respondents draw the correct conclusions?
- Is a graphical (*Q/A*) or a numerical approach (positioning in figure) preferred?

Eight students of the faculty of Industrial Design Engineering (all master students) have been requested to use the model. Eight is an appropriate amount of subjects for executing a usability study [20]. The subjects have been asked to perform three assignments for different products: a laptop, a cellular telephone and a vacuum cleaner. The assignment encompasses the use of the method and drawing thermal design conclusions. The design conclusions focused on passive vs. active cooling and on thermally critical or non-critical.

The subjects received an explanation of the method on one sheet of paper, including the graph as shown in Figure 5. Three products have been presented each in a different way, a photo, a drawing and a real product. The subjects had the disposal of a ruler to roughly measure the dimensions for the real product, the dimensions of the other products have been given in the assignment and the power consumption has been given. The respondents have then been asked to derive conclusions for each product. The analysis could have been done either by positioning the designs in the graph or by using the formula *Q/A*. calculation of the product surface. The results are as follows:

Understand ability and errors:

- Uncertain calculation of *A*. Some respondents calculated only the surface of the product's largest face. Others calculated volume instead of surface.
- Difficulties occurred with converting units from cm^2 to m^2.
- Some subjects showed problems with reading the logarithmic scale.

Drawing conclusions:

- 4 out of 8 respondents correctly assigned the cooling categories to all three products.
- 6 out of 8 derived the right conclusions regarding thermally critical/non-critical.

Graphical vs. numerical:

- 3 out of 8 respondents used the graph only, 2 only calculations and 3 used both methods.
- 5 out of 8 used the method correctly. Others used not the minimum enclosing box but another type of area however used the outcome in the correct way to draw design conclusions.

In general, most users experienced at least a few problems while making the assignments with the model. The model itself was understood with few problems. Its cause and goals are understood by all respondents. Both the graph and formula can be used and result in drawing the correct conclusions. However, not all users find the correct conclusion. The method must therefore be improved with regard to calculation of *A* (surface area of the minimum enclosing box). Problems with converting units and reading logarithmic are educational issues.

5.2 Interviews

To find out more about the use of the model in a professional context, six professional designers have been interviewed. In all interviews the model has been valued as a good tool for quick evaluation of passive versus active cooling. It thus helps to decide whether or not to use a fan in a product and wil in that case be an improvement in the conceptual phase of design.

There were several comments on the fact that the model does not work on a detail level and that it is only a basic rule, and can not be used as an absolute answer. When the heat dissipation of components is critical, this model does not predict local hotspots such as a transistor which must be specifically taken into account. We can conclude that the designer must therefore always take hotspots into account in detail analysis. The model however does show whether the hotspot can be passively cooled relatively easy by means of spreading the heat, e.g. through the encasing.

Another point mentioned is that some products that become very hot such as lamps etc. often fall in zone 1 and do not have to use a fan because of the materials that have been used. In addition it is seen important to consider the dissipated heat of the product. In the case of an electromotor e.g. the total power withdrawn is not the same as the dissipated power because part of the power is converted into mechanical movement. Efficiency thus plays a significant role in defining the dissipated power Q.

The respondents noticed that the model doesn't work for products with a periodical dutycycle and that the model does not take into account transient temperature behavior. This is important in the case of products with a short dutycycle but high power use (electronic screwdriver or drill, often products with an electromotor). Follow up studies should therefore take into account the effect of energy use per dutycycle.

A final comment is that cooling can be done in several ways which makes it necessary to optimise the use of the model by taking into account more preconditions as to adapt to different design situations. As an example: changing air properties with altitude, using cooling fins or attaching hotspots to the encasing, open versus closed encasing, including the possibility to evaluate maximum temperature and to change temperature and encasing material

8 CONCLUSIONS AND RECOMMENDATIONS

We have developed a simple model that can practically be used for first order exploration of thermal design of electronic products. The model gives an indication whether or not the existing concept demands more detailed exploration of the temperature development in the device. The model can also be used by the designer to discuss if it is theoretically possible to naturally cool the product dependent on the ergonomic temperature criteria of the encasing. The usability of the method has been tested by experiments with 8 design students and has been verified by interviewing six expert designers. The present results suggest that the model can be effectively used in the primary exploration of the thermal design of an electronic product. However, several improvements are needed on the area of practical usage and preconditions of use.

Future research will focus on a more detailed level of first order thermal evaluation. A model will be developed that takes into account transient hotspot temperature development, an aspect that will give more insight in the thermal behavior of an electronic concept design. It is expected that the use of such a simple mathematical model will result in an improved (faster) conceptualisation process.

REFERENCES

[1] Coxe W.K., Solbrekken G.L., Yazawa K. and Bar-Cohen A. Experimental modeling of the passive cooling limit of notebook computers. In *Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM, Vol. 8,* San Diego, May 2002, pp.15-21 (IEEE, Piscataway).

[2] Ishizuka M. and Hayama S. Application of a semi-empirical approach to the thermal design of electronic equipment. In *Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM, Vol. 7,* Las Vegas, May 2000, pp.99-106 (IEEE, Piscataway).

[3] Ishizuka M., Peng G. and Kitamura Y. Study on the natural air cooling of electronic equipment casings: Effects of the outlet vent and the power heater locations on the cooling capability. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* 2002, 216(3), 269-276.

[4] Teertstra P., Yovanovich M.M. and Culham J.R. Modeling of natural convection in electronic enclosures. In *Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM, Vol. 9,* Las Vegas, June 2004, pp.140-149 (IEEE, Piscataway).

[5] Farkas G., Poppe A., Kollar E. and Stehouwer P. Dynamic compact models of cooling mounts for fast board level design. In *Annual IEEE Semiconductor Thermal Measurement and Management Symposium, STHERM, Vol. 19,* San Jose, March 2003, pp.255-262 (IEEE, Piscataway).

[6] de Jong E.C.W, Ferreira J.A. and Bauer, P. Thermal model extraction as means to thermal management improvement in PCB assembled power converters. In *Proceedings of the Power Conversion Intelligent Motion Conference, PCIM, Vol. 1,* Nuremberg, June 2005.

[7] Kitahara T. and Nakai K. Thermal analysis for high-performance small devices. In *International Conference on Multichip Modules, Vol.* 6, Denver, April 1997, pp.296-302 (IEEE, Piscataway).

[8] Li Q., Grant S.P., Osvaldo Q.M. and Xie Y.M. Shape and topology design for heat conduction by evolutionary structural optimization. *International Journal of Heat and Mass Transfer,* 1999, 42(17), 3361-3371.

[9] Minichiello A. Flow network modeling: a case study in expedient system prototyping. In *Proceedings of the Intersociety Conference Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM, Vol. 7,* Glasgow, July 2000, pp.70-77 (IEEE, Piscataway).

[10] Yazawa K. and Bar-Cohen A. Energy efficient cooling of notebook computers. In *Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM, Vol. 8,* San Diego, May 2002, pp.785-791 (IEEE, Piscataway).

[11] Baek M. and Lee J. Thermal design for notebook pc by using thermal analysis. In *International Flotherm User Conference, Vol. 9,* Orlando, October 2000.

[12] Lasance C.M. The conceivable accuracy of experimental and numerical thermal analyses of electronic systems. *IEEE Transactions on Components and Packaging Technologies,* 2001, pp.180-198.

[13] Lasance C.M. Thermally driven reliability issues in microelectronic systems: status-quo and challenges. *Microelectronics Reliability,* 2003, 43(12), 1969-1974.

[14] Bergles A.E. Evolution of cooling technology for electrical, electronic, and microelectronic equipment. *IEEE Transactions on Components and Packaging Technologies,* 2003, 26(1), 6-15.

[15] Remsburg R. *Thermal design of electronic equipment,* 2001 (CRC Press, Boca Raton).

[16] Ellison G.N. *Thermal computations for electric equipment,* 1984 (Van Nostrand Reinhold, New York).

[17] Holman J.P. *Heat transfer,* 2002 (McGraw-Hill, Boston).

[18] Kordyban T. *Hot Air Rises and Heat Sinks: Everything You Know About Cooling Electronics Is Wrong,* 1998 (American Society of Mechanical Engineers, New York).

[19] Langhaar H. L. *Dimensional analysis and theory of models,* 1980 (Krieger, New York).

[20] Kanis H. and Arisz, H.J. How many participants: a simple means for concurrent monitoring. In *Proceedings of the International Ergonomics Association/Human Factors and Ergonomics Society, IEA/HFES, Vol. 44,* San Diego, July-August 2000, pp.6637-6640.

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