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Thermal Modelling in Product Design using FloEFD^{TM}Pro: From Concept to Reality

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***Abstract*—Heat generation in active, powered systems as well as heat absorption from ambient environment can significantly degrade product performance if not properly considered. High operating temperature can shorten the service life of components considerably and amplify the effects of air moisture hence causes severe reliability failures. This paper demonstrates how early consideration of thermal performance during the product development stage can affect the form, fit and function of a product. Thermal predictions presented in this paper are accomplished using commercially available computational fluid dynamics (CFD) simulation software – [1]FloEFD^{TM}Pro. Without the need for in-depth knowledge in CFD formulation and theories, thermal performance and dissipation of product can be predicted to aid mechanical design making products more robust and reliable.**

***Index Terms*— Computational fluid dynamics, FloEFD^{TM}Pro, Thermal dissipation, Thermal simulation**

I. Introduction

Along the product design lifecycle, it is imperative to consider thermal performance during the conceptual design stage. Such practice is applicable in all industries not limited to electronics, automotive, shipping as well as aerospace and defense. Electronics systems generate heat, mechanical packaging absorbs heat from the ambient and air movement in the surrounding environment can affect thermal transfer. All these factors that have to be taken into account during the infant stage of product design. Due to the fact that physical testing is too costly with the anticipated number of design iterations and almost impossible during conceptual design, computer simulated predictions play an important role. In this paper, case studies are presented to demonstrate how early consideration of thermal performance during the product development stage can affect the form, fit and function of a final product.

II. Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is becoming increasingly common in recent decades as a tool to predict thermal transfer. Thermal transfer usually occurs either when two bodies are in direct contact or indirectly via a fluid medium. Therefore the governing differential equations are similar to governing differential equations for fluid flow. The main intention of a CFD tool is to solve the transport of mass,

$$\frac{D\rho}{Dt} + \rho\nabla u = 0 \tag{1}$$

transport of momentum;

$$\rho\left[\frac{Du}{Dt} + (u \cdot \nabla)u\right] + \nabla P = \nabla^2 u + \rho B \tag{2}$$

and energy in moving fluid numerically [1] where ρ is the density, u is the velocity, P is the pressure and B is the body force per unit mass of the fluid. The energy equation also dictates the fluid behaviour due to other influences such as heat transfer and chemical reactions. In this paper, the source of energy transfer within the system is solely due to heat transfer. Three modes of heat transfer *i.e.* conduction, convection and radiation are each governed by,

$$Q = -\kappa A \nabla T \tag{3}$$

$$Q = hA\Delta T \tag{4}$$

and,

$$Q = A\varepsilon T^4 \tag{5}$$

respectively, where Q is the heat transferred in Watts, T is the temperature, A is the surface area, κ is the material conductivity, h is the heat transfer coefficient and ε is material emissivity.

A commercially available computational fluid dynamics (CFD) simulation software – FloEFD^{TM}Pro is used for all the thermal predictions presented in this paper. FloEFD^{TM}Pro is easily distinguished from conventional CFD simulation software whereby the software is designed for the interest of engineers to focus on the thermal performance and fluid dynamics of a product, without the need for in-depth knowledge in CFD formulation and theories [2]. FloEFD^{TM}Pro is tightly integrated with mechanical computer-aided design (CAD) software such as [2] Pro/ENGINEER® which allows seamless integration between product design and simulation of thermal performance [2].

The next section of the paper presents the thermal design requirements and considerations taken into account during the development of a plastic casing for a telecommunication device that can be used both indoor and outdoor.

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[1]FloEFD^{TM}Pro is a registered trademark of Mentor Graphics Corporation.

[2] Pro/ENGINEER® is a registered trademark of Parametric Technology Corporation.

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III. Outdoor Casing for Telecommunication Application

Fig. 1. Examples of a telecommunication device placed indoor and outdoor © MIMOS Berhad 2009.

Fig. 1 shows some examples of telecommunication devices used at both indoor as well as outdoor applications. When the device is used outdoor, it is subjected to thermal heating from the environment *i.e*. solar radiation. The changes in air temperature causes pressure differences between the internal and external of the device. Therefore the device requires a robust casing that will not only enclose the main printed circuit board (PCB) assembly, provide support to the chassis that holds the PCB but able to play a role of protection against water ingression. The main intent of this paper is to demonstrate the development of such a mechanical casing for an outdoor telecommunication device, considering the thermal performance as early as during the conceptual design.

It is common that the casing of the device houses PCB assembly which is held by a chassis. On the PCB, there are some heat generating components such as the main processor, and Ethernet processor that can produce considerable amount of heat during operation. Metal heat sinks in the device provides thermal sinking for the heat accumulated from within the device, which will in turn be transferred out of the system to the ambient environment. The casing device which encloses the assembly providing sealing against water ingression is preferably made of injection molded plastic due to electromagnetic requirements. However (injection molded) plastic casing usually has a higher heat capacity compared to that of most common metals. This poses a negative effect to the thermal performance of the device. Designed air vents on the casing enable air flow into and out of the device, fostering natural convection between the components and the surrounding environment but violate the IEC IP54 (indoor) and IEC IP65 (outdoor) [3] sealing requirements. All these factors need to be considered when designing a product, in this case a suitable casing for the device as accumulation of thermal energy within the casing can cause temperature to build up and subsequently failure of components.

The next section of the paper describes the characterization of the thermal performance of the device by conducting a series of temperature measurements

IV. Thermal Test

The main intent of this thermal test is to characterize the thermal performance of a few components on the PCB. These components are significant heat generating components on the PCB. Fig. 2 shows the equipments used to measure the surface temperature of the abovementioned components. Temperature is measured using the Fluke 568 IR Thermometer. The Fluke 568 thermometer is a 2-in-1 Infra-red (IR) and contact digital thermometer. Two sets of readings were obtained through IR measurement and Type-K thermocouple bead probe attached to the location of interest for the case where the casing is removed. The measurements were collected indoor at ambient temperature of 22.5 ºC, operating for an hour to achieve steady state.

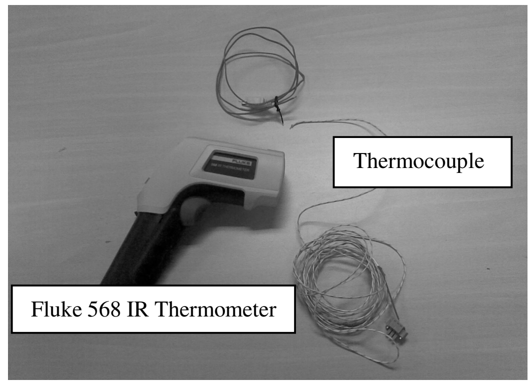

Fig. 2. Equipment used for thermal test. © MIMOS Berhad 2009.

Table 1 - Comparison of component temperature measured using IR probe and K-Type thermocouple.

Measured Temperature (°C)	IR probe	K-type thermocouple
Location 1	44	45
Location 2	37	41
Location 3	31	32
Location 4	36	38

Table 1 shows a comparison of measured temperature measured using the IR laser probe and K-Type thermocouple bead attached to each location. The results showed reasonable agreement between the two methods of measurements produced by the equipment. The main reason the components on the PCB were measured without the casing enclosed is to characterize the thermal performance which will be used as a *sanity check* against the prediction produced by CFD simulations. The next section presents the CFD modelling of the device and comparison of measured and predicted results.

V. CFD Simulations

This section describes the setting up of the simulation model in FloEFD™Pro. CAD model is transferred to FloEFD™Pro from Pro/ENGINEER® seamlessly within a few mouse clicks. Fig. 3 shows the graphical user interface of flow analysis having the common Pro/ENGINEER® interface. The modelling of the flow is aided by a wizard, which creates the boundary conditions, defines the fluid properties and sets the initial conditions *e.g*. temperature, pressure and velocities.

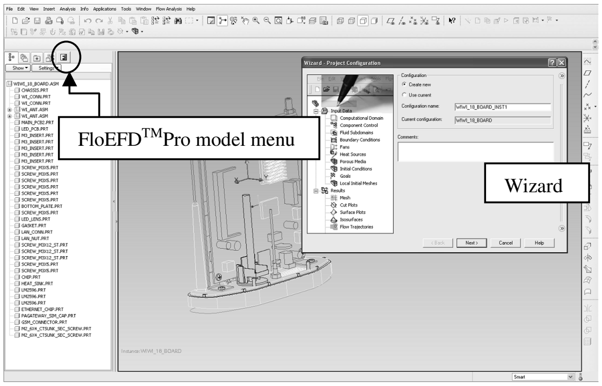

Fig. 3. CFD modelling using FloEFD™Pro in Pro/ENGINEER® environment. © MIMOS Berhad 2009.

To model the thermal performance of the plastic casing of the device during operation, an external analysis has been setup for the device. An external flow analysis considers the fluid flow (in this case air) around the model such that the heat transfer from the solid (device) to the moving air can be modelled. Radiative heat transfer can be modelled by specifying the emissivity properties of solid surfaces so that the software will consider heat absorption. The analysis will also consider air movement within the device, if any therefore simulates the thermal dissipation from the heat generating components to the outside environment. Table 2 shows the thermal properties of materials used in the analysis.

Table 2 - Material properties of solid used in the model.

Material	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)
Steel	7870	51.9	472
FR4	1200	0.3	880
Molded ABS	805	0.19	2000
Silicone Rubber	1160	0.22	1300 – 1460
BGA	2000	1.5	700
Copper Tungsten	17170	160	149
Aluminium	2680	140	921
Typical SOIC	2000	0.4	350

Table 3 - Comparison between measured and CFD predicted component temperature.

Temperature (°C)	Measured	CFD Prediction
Location 1	44	50
Location 2	37	36
Location 3	31	34

With the heat source information entered to the model, the CFD results at steady state were checked against the measured values presented in the previous section whereby the casing of the device is removed. Reasonable agreement between the predictions and measurements can be observed in Table 2 giving confidence to the validity of the CFD model. Next the performance of the casing is simulated for both indoor and outdoor conditions. Ambient temperature of 23 °C is used for indoor simulation while 34 °C is used for outdoor simulation. FloEFD™Pro can model radiation from the sun by specifying the location (latitude) and time of the year and day which defines the solstice and equinox automatically. By specifying radiative surface properties, thermal absorption can be simulated hence giving a much more realistic outdoor simulation. Fig 4 shows the setup window for solar radiation.

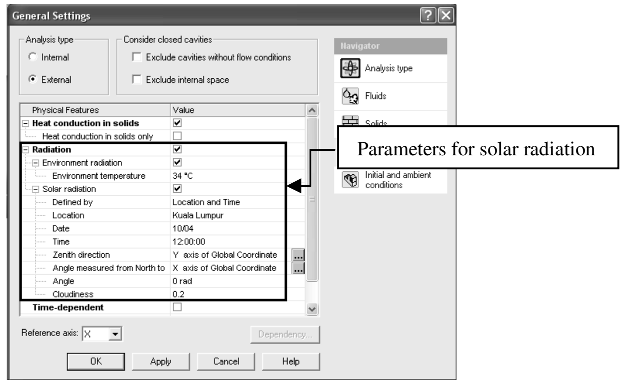

Fig. 4. Setup for solar radiation in FloEFD™Pro. [4] © MIMOS Berhad 2009.

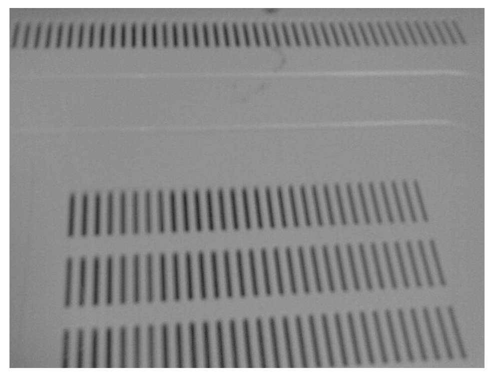

Fig. 5. Designed air vents at the back of the casing. © MIMOS Berhad 2009.

Fig. 5 shows the picture of the plastic casing developed in Pro/ENGINEER®. Air vents were designed at the back of the casing initially but was not desirable as it violated the water sealing requirements. However, the absence of air vents has significant effect on the thermal performance. Hence, the aim of the CFD simulation is to decide whether air vents can be avoided at the conceptual stage of the design without having to test prototypes.

VI. Discussion of Results

A. Indoor

The main intent of the CFD simulation is to determine i) the surface temperature of the plastic casing, and ii) the highest temperature of the component on the PCB assembly. The plastic casing is required to dissipate sufficient heat so that heat is not accumulated within the enclosure. The air temperature within the enclosure is best kept below 60 °C to minimize the thermal stress inside the electrical components and to maintain the processor temperature well below the threshold. To model indoor application, the steady state solution for the device (with the casing attached) is obtained

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at an ambient temperature of 23 °C. The operating state being the same as the (exposed) model presented in the previous section. In this study, the air vents on the casing were removed to simulate the *worst case scenario*. Fig. 6 shows the cut plot for temperature of air within the enclosure at steady state.

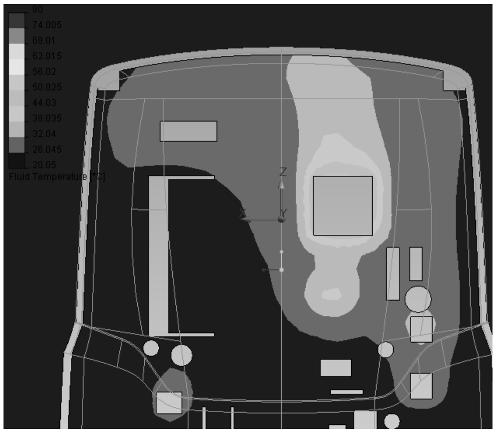

Fig. 6. Cut plot of temperature contour for air inside the enclosure. © MIMOS Berhad 2009.

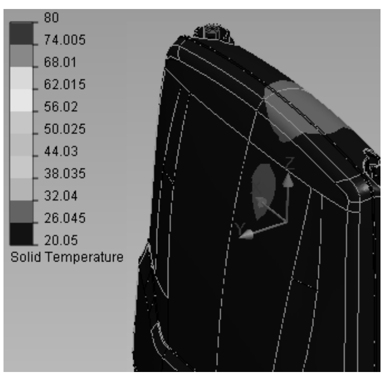

Fig. 7. Temperature contour at the surface of the plastic casing. © MIMOS Berhad 2009.

It can be seen that the highest temperature inside the enclosure is approximately 50°C around the hottest component. A quick check on the surface temperature of the plastic casing shown in Fig. 7, temperature gradient could hardly be seen. The results give an indication such that the plastic casing absence of air vents is suitable for the device for indoor applications.

B. Outdoor

This section presents the CFD simulations results for the device operating outdoor under solar radiation and environment heating. In parallel to the development of the CFD model in FloEFD^{TM}Pro, an outdoor thermal test was conducted. In this test, an empty box (made of plastic, approximately the intended size) with no air vents commonly used for outdoor applications was put under the sun for more than 6 hours (See Fig. 8). Ambient temperature, surface temperature of the casing (box) and temperature within the enclosure were collected at 2 hour intervals. The surface temperature of the casing was measured using the IR probe and the temperature within the enclosure was measured using the K-type thermocouple bead. Both temperatures were collected using the Fluke 568 IR thermometer.

Fig. 8. Outdoor thermal test. © MIMOS Berhad 2009.

Table 4 - Outdoor ambient temperature, casing temperature and internal air temperature of plastic casing.

Day	Time	Ambient Temperature (ºC)	Casing Temperature (ºC)	Internal temperature (ºC)
1	1000	29.2	34.9	32.9
	1200	35.6	50.8	42.2
	1400	36.6	47.7	40.6
	1600	33.0	38	34.2
2	1000	29.6	34.3	31.7
	1200	28.4	30.1	28.6
	1400	34.7	42.5	33.0
	1600	29.2	32.6	29.2
3	1000	29.2	32.1	30.3
	1200	31.1	38.5	30.8
	1400	34.7	37.2	33.1
	1600	31.2	33.8	30.7

This test aims to give a better understanding of the levels of temperature an empty plastic casing can achieve when put under the sun for more than 6 hours. Table 3 shows the results of temperature collected in 3 days over the same period and time intervals. Results show hottest temperature of approximately 42 °C within the enclosure giving some confidence to the design.

To simulate outdoor application, the CFD model is then updated with an environment temperature of 34°C and solar radiation using Kuala Lumpur as the location, during mid-day so that the direction of solar radiation is directly from the top of the device. An initial air velocity of 2.5 m/s in the *x*-direction is added to the model to simulate the wind speed according to the weather conditions. Fig. 9 shows the cut plot for temperature of air within the enclosure at steady state. It can be seen that the highest temperature inside the enclosure is approximately 56 °C around the hottest component, which is higher compared to indoor. Additional heat is absorbed from the environment, which in turn heated up the PCB.

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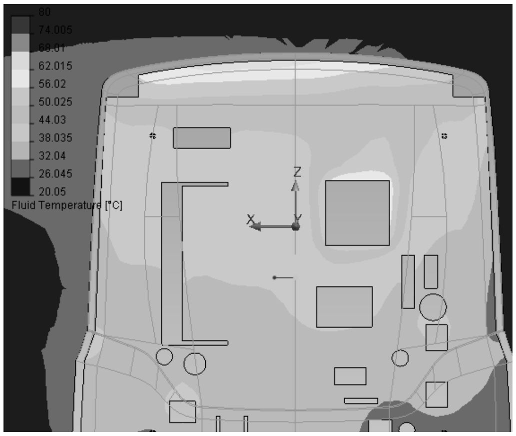

Fig. 9. Cut plot of temperature contour for air inside the enclosure. © MIMOS Berhad 2009.

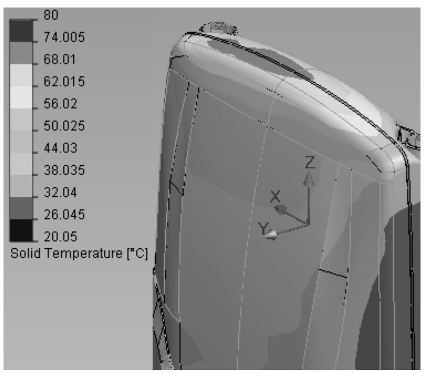

Fig. 10. Temperature contour at the surface of the plastic casing. © MIMOS Berhad 2009.

The surface temperature of the plastic casing shown in Fig. 10 shows a much higher value of close to 70 °C for outdoor application. However, it must be noted that the simulated predictions are based on steady state, which is more severe compared to actual situation. The results give an indication such that the plastic casing absence of air vents is still suitable for the device for outdoor applications. These simulated results contributed to the development in such a way that they showed that air vents are unnecessary. When such a decision can be made at such an early stage of the product design, considerable amount of development costs and resources are saved.

VII. Conclusion

The work presented in this paper has demonstrated the role played by CFD in the development of a plastic casing for the device starting from conceptual stage. The CFD results complement the outdoor thermal test by allowing more design options to be tested (simulated) before actually building prototypes. Nonetheless, simulation model enable design iterations to be implementation at a lower cost. This piece of work has also demonstrated the use of advanced analysis method *i.e*. CFD using FloEFD^{TM}Pro during the mechanical design of the casing of a outdoor telecommunication device. The software is distinguished from conventional CFD simulation software whereby the software is designed for the ease of use of engineers to test and prove their design at an early stage of product development and give indicative results before prototyping.

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