VTT PUBLICATIONS 320

Verification of the thermal design of electronic equipment

Risto Hienonen, Matti Karjalainen & Raija Lankinen
VTT Automation

TECHNICAL RESEARCH CENTRE OF FINLAND
ESPOO 1997

ISBN 951–38–5072–2
ISSN 1235–0621

JULKAISIJA – UTGIVARE – PUBLISHER

Valtion teknillinen tutkimuskeskus (VTT), Vuorimiehentie 5, PL 2000, 02044 VTT
puh. vaihde (09) 4561, faksi (09) 456 4374

Statens tekniska forskningscentral (VTT), Bergmansvägen 5, PB 2000, 02044 VTT
tel. växel (09) 4561, fax (09) 456 4374

Technical Research Centre of Finland (VTT), Vuorimiehentie 5, P.O. Box 2000,
FIN–02044 VTT Finland
phone internat. +358 9 4561, fax +358 9 456 4374

VTT Automaatio, ProTechno, Otakaari 7 B, PL 13051, 02044 VTT
puh. vaihde (09) 4561, faksi (09) 456 7042
Internet: http://www.vtt.fi/aut/

VTT, Automation, ProTechno, Otsvängen 7 B, PB 13051, FIN–02044 VTT
tel. växel (09) 4561, fax (09) 456 7042
Internet: http://www.vtt.fi/aut/pro

VTT, Automation, ProTechno, Otakaari 7 B, P.O. Box 13051, FIN–02044 VTT Finland
phone internat. +358 9 4561, fax +358 9 456 7042
Internet: http://www.vtt.fi/aut/pro

Technical editing Leena Ukskoski

LIBELLA PAINOPALVELU OY, ESPOO 1997

Hienonen, Risto, Karjalainen, Matti & Lankinen, Raija. Verification of the thermal design of electronic equipment. Espoo 1997, Technical Research Centre of Finland, VTT Publications 320. 86 p. + app. 13 p.

UDC 621.38:536.5
Keywords thermal design, verification, thermal audite, electronic equipment, electronics, cool, quality, quality control, thermal model, temperature measurement, tests, environmental tests, Finland

ABSTRACT

The project “Elektroniikkalaitteen lämpösuunnittelun verifiointi” (“Verification of the thermal design of electronic equipment”) studied the methodology to be followed in the verification of thermal design of electronic equipment. This project forms part of the “Cool Electronics” research programme funded by TEKES, the Finnish Technology Development Centre. This project was carried out jointly by VTT Automation, Lappeenranta University of Technology, Nokia Research Center and ABB Industry Oy VSD-Technology.

The thermal design of electronic equipment has a significant impact on the cost, reliability, tolerance to different environments, selection of components and materials, and ergonomics of the product. This report describes the method for verification of thermal design. It assesses the goals set for thermal design, environmental requirements, technical implementation of the design, thermal simulation and modelling, and design qualification testing and the measurements needed.

The verification method covers all packaging levels of electronic equipment from the system level to the electronic component level. The method described in this report can be used as part of the quality system of a corporation. The report includes information about the measurement and test methods needed in the verification process. Some measurement methods for the temperature, flow and pressure of air are described.

The report is available both in English (VTT Publications 320) and in Finnish (VTT Julkaisuja 824).

FOREWORD

The thermal design of electronic equipment has become one of the most important aspects of product design that ensure reliability of the device and thus its ability to compete on a demanding market. The packaging density has risen in all major electronic product categories - telecommunications equipment, computers, automation and power electronics - to such a degree that the waste heat of the electronics can no longer be removed without advanced heat transfer and cooling techniques.

The purpose of this project has been to develop a verification method that makes the thermal design process more controllable. Whether novice or expert in the field of thermal design, the user of the method should be able to assess the goals of the thermal design, the correctness of the thermal design process and the outcome of the design.

Because thermal design and thermal analysis techniques still suffer many shortcomings, not least a lack of data on the thermal properties of materials and components, the design calculations and numerical simulations must be supported by well-controlled testing and measurement technology. The report includes information about the measurement and test methods needed in the verification process. Some measurement methods for the temperature, air flow and pressure of air are described.

This publication is the final report of the “Verification of thermal design of electronic equipment” project which forms part of the “Cool Electronics” research programme. The programme funded by the Finnish Technology Development Centre (TEKES) begun in May 1996. The project was funded by TEKES, VTT Automation, ABB Industry Oy VSD-Technology and the Nokia Research Center.

The KOTEL Society’s Working Group “TR 18 - Thermal design of electronics” has supported the project group and the management board of the project. The basic contents of this report were drawn up during meetings of the KOTEL working group. In December 1996 the project group arranged jointly with the KOTEL working group a seminar on “Measurements in the thermal design of electronics”. The verification method presented in this report was tested in three thermal design projects: One for sample acquisition tools for a spacecraft lander, one for a low power frequency converter, and the third for a medium size electronics cabinet for use in the Tropics.

The board members of the project were

Risto Hienonen	VTT Automation, chairman
Tuija Järvinen	Nokia Research Center
Vesa Kyyhkynen	ABB Industry Oy VSD-Technology
Raija Lankinen	Lappeenranta University of Technology, Energy Technology Department

Project manager Risto Hienonen, Senior Research Scientist at VTT Automation, headed the project and wrote chapters 1 and 2, sections 3.1, 3.2 and 6.1 to 6.4. Section 6.4 is based on the text /6.6/ by Chief Research Scientist Olavi Keski-Rahkonen from VTT Building Technology. Research Scientist Matti Karjalainen from VTT Automation wrote sections 3.3 to 3.6, and chapters 4 and 5. Senior Assistant Raija Lankinen from Lappeenranta University of Technology wrote sections 6.5, 6.6 and Appendix 1. This report was translated in English by Research Scientist Kai Viherkanto, Research Scientist Paul Stigell VTT Automation, and Senior Assistant Raija Lankinen. Contents and linguistic inspection of translation was done by Professor Gilbert W. Leppelmeier and B.Sc. Adelaide Lönnberg.

The following members of the KOTEL society's working group "TR 18 - Thermal design of electronics" took part in the brain-storming sessions from which this report emerged.

Risto Hienonen	VTT Automation
Tuija Järvinen	Nokia Research Center
Matti Karjalainen	VTT Automation
CAI Kabrell	Nokia Research Center
Matti Kokko	Nokia Telecommunications Oy Radio Access Systems
Mario Lopez-Jorkama	VTT Automation
Liisa Nyblom	Finnyards Ltd. Electronics
Kari Ojala	Nokia Research Center
Anu Parviainen	Nokia Telecommunications Oy Fixed Access Systems

Both on behalf of the board of this project and personally, I would like to thank all who took part in the project, including project team members, members of the review teams and financers.

Espoo, Finland 30.10.1997

Risto Hienonen
project manager

Contact information :

VTT Automation
ProTechno

P.O. Box 13051
02044 VTT, Finland

telephone ***+358-9-456 6534***
telefax ***+358-9-456 7042***
Internet ***Risto.Hienonen@vtt.fi***
Matti.Karjalainen@vtt.fi
Raija.Lankinen@lut.fi

CONTENTS

1 PURPOSE OF VERIFICATION OF THERMAL DESIGN

The thermal design of electronic equipment is one of the most important parts of product design that affect decisively the reliability and operating characteristics of the unit. Thermal design is closely related to the mechanical design and design for environmental endurance. It is also linked to the thermal and environmental testing that verify the design. The verification of thermal design consists of whatever activities will ensure that the results of thermal design meet the requirements and that the product performs according to its specifications in all environments it encounters during its service life.

The purpose of the verification activities is to assure that

- the product design process is expedient and the results it generates are correct
- the design and the hardware meet the requirements set for the thermal design
- the thermal model is suitable for the analysis it is used for
- correct measurements and tests are performed
- possible reliability risks are detected
- different parts of product design are brought together
- the design process has means to take corrective actions.

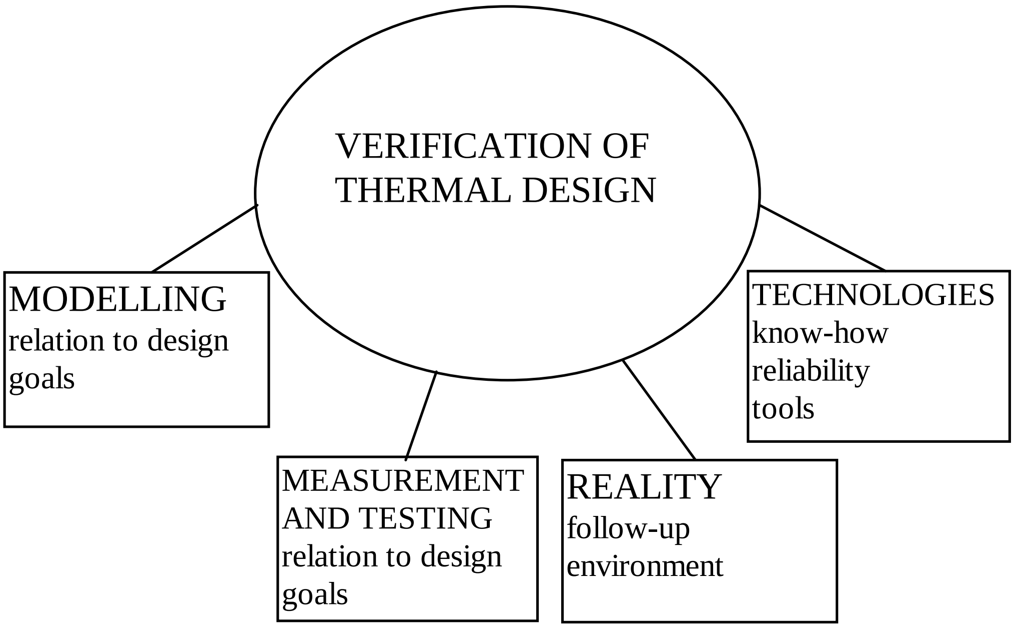


Figure 1. Verification objects in thermal design.

Thermal design and its verification are a crucial part of the overall research and development process, because thermal control solutions influence decisively the technologies that can or must be used in the product. It is important that thermal, mechanical, ergonomic and electromagnetic design characteristics are dealt with concurrently with other aspects of the product design.

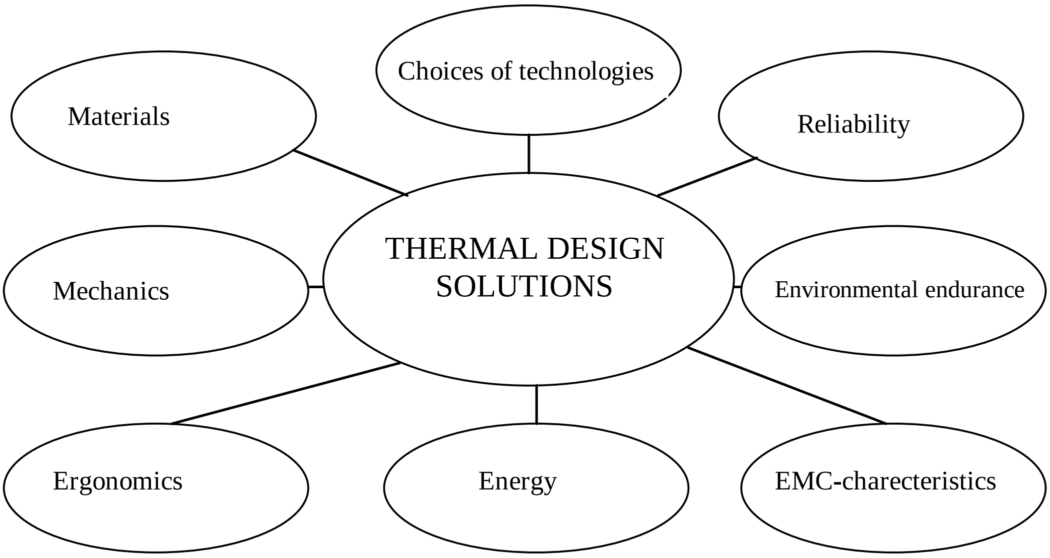


Figure 2. Influence of thermal design on the product.

The thermal characteristics affect the basic reliability of the device. Most faults in electronics are somehow related to thermal stresses and excessive moisture levels. (Fig. 4, page 21). Almost all the properties of components and materials change with the temperature and humidity; controlling these variables is an important part of product design and must be taken into account also in thermal design. The removal of heat from equipment invariably limits the scope of design in the areas of mechanics, ergonomics, electromagnetic shielding and electronic circuits. On the other hand, thermal design solutions can greatly improve the product’s functionality, reliability and corrosion resistance if they are included in the design goals. The goal of the verification process is to check all such goals in order to assure that the product meets its objectives and all relevant risks are identified. The next chapter describes how thermal design and the activities related to its verification can be incorporated as a natural part of product definition and development. This would enable the thermal constraints and possibilities for thermal design to be taken into account before the design is “frozen” into a configuration leading to poor reliability and uneconomical implementation.

2 VERIFICATION

2.1 INCORPORATING VERIFICATION INTO PRODUCT DESIGN

Verification activities are performed during different phases of product development and the thermal design process. They comprise a stepwise multi-stage refining process as the design matures, allowing the design to be changed and redirected. In order to get the full benefit of verification, both it and the thermal design must be incorporated from the start into the research and development process. I.e. the thermal design expert must be involved in the product definition and development from its inception.

Verification must be active in nature so that it raises the quality of the product and not only evokes a passive response of checking chosen solutions. Raising questions already at the idea-generating and design phases of product design as to how thermal design could improve the product capabilities, and what should be avoided, leads to much better overall solutions than passive fulfilment of the given requirements.

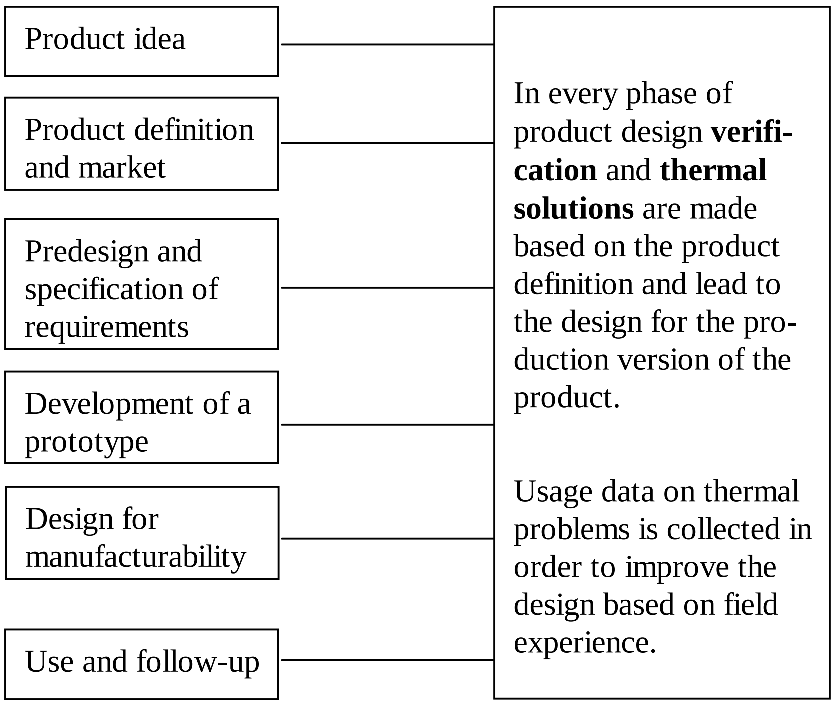


Figure 3. Implementation of thermal design in product design.

The verification process examines the goal setting of the thermal design, the thermal design and its results from different perspectives:

- thermal requirements for the product
- widest possible use of thermal control engineering; have all possibilities to improve the product been utilised?
- correctness of the thermal design; finding basic mistakes
- design data and test measurement data,
- is it technically and economically possible to further improve the product?

Successful verification requires that the person performing it learn all about the general goals of design, the type and nature of the product, the history of the product design, etc. Once he has a clear picture of the verification task, a verification process can be planned that fits the needs of the particular project.

A sufficient number of thermal designers and designers in other fields of product design should participate in thermal design and test reviews, so that all aspects of product design that depend on successful thermal design are dealt with. The participation of a thermal designer who is an outsider to the project under review gives added value to the review.

2.2 CHOOSING THE LEVEL OF CONTENTS OF VERIFICATION

Thermal design verification is performed at different levels of content during the various design phases of electronic equipment.

During goal setting the primary concern is to identify the physical conditions under which the product will be used, the internal conditions of the product and the technical possibilities to achieve the goals, taking into account the restrictions imposed by e.g. the mechanical design or the available components.

At the start of the design phase existing knowledge and available data on the thermal characteristics of the materials and components are checked. The margins of the thermal design are set at this stage. As the design develops into more concrete and well defined physical representation, the level of accuracy and level of physical representation of the verification are increased. Here focus is primarily on information concerning the characteristics of materials and components, technical solutions for the thermal control design, the correctness of a possible thermal model and how well the results of tests and simulations meet the specifications.

At the end of the design phase the verification focuses on assessment of the final design and the results of the prototype tests, and on decisions about possible corrective action if needed. Closing the verification process at the end of the design phase includes decisions on how to follow up the product performance through customer feedback, for example, during the product's warranty period.

Verification activities in the different phases of product design.

1 Goal setting for the thermal design of electronic equipment
Ensuring that thermal design is involved in all phases of the product design.
Definition of concrete goals (power, temperature limits, mechanics, materials, environments, testability, other case-by-case requirements and taking a stand on the usage of physical models and tests).
Assessment of the reasonableness of the goals and of the physical limits.
Comparison of the goals with design and field experience.
Purposeful employment of thermal control technology; assessing whether the design goals include all features of the product that could be improved through thermal design (e.g. increased tolerance of environmental conditions and reliability). One principle could be to make the inside conditions of the equipment as moderate as possible.
Understanding the effects of the operating environments.
Outlining the general level of precision of the design.
Agreeing on the phases and deadlines for verification activities and linking them to the other design activities.

2 Start of the design phase
Selection of design techniques and design tools.
Recognising boundary conditions and external constraints (construction, environment etc.)
Selection of properties of materials and components for the thermal design.
Definition of interfaces, mechanical design and materials.
Definition of design margins to ensure that the inside temperature limits given by the component manufacturer are not exceeded and that the goals (derating) set for the improvement of reliability are achieved.

Suitability of a thermal mathematical model and the thermal design for solving the problem at hand.

Usability of information gained from investigation of structural models (e.g. cardboard mock-up).

Representability of the model compared with the physical device.

Correlation between the preliminary results and the design goals.

3 Middle part of the design phase

All relevant boundary conditions, interfaces, design margins and possible computer model are defined to meet the requirements. These are compared with possible analysis or test results and the representability compared with the physical realisation in detail.

Sources of possible error of thermal design are evaluated.

If possible, tests and test measurements are performed using prototypes and, if possible, structural models.

Decisions are made ranging from design changes to continuation of the product design and design goals.

4 Final design phase and production phase

Final definition of boundary conditions, interfaces and design margins. The thermal design and the thermal mathematical model have been developed to the best attainable level at this phase of the design project. All aspects concerning the thermal design, testing and analysis are examined.

The design is compared with the design goals.

The planned tests and measurements are performed and the results are compared with those of the thermal design and, possibly, the results of computer simulations.

If required, acceptance tests and measurements are performed in an external test facility or by the customer.

A decision is made whether the design is acceptable or not. If not, corrective actions must be defined.

5 Use of field information
The plan for utilisation of the field information (feedback) is approved. Questions like “will information be collected?” and “how is the information collected?” are answered. Field feedback and failure information are compared with the results of the thermal design, thermal analysis and thermal testing. Causes for possible discrepancies are determined, such as too coarse a thermal design accuracy, properties of the materials and components, or changes introduced to the equipment design during manufacture. The field information also contains information about the following design aspects: environmental conditions, mechanical design, ergonomics, safety, user needs, electromagnetic compatibility (EMC), electrical and electronics design and ageing of materials. All these have an impact on thermal design. It is ensured that the field information is used in improvements made to the product and to the design of subsequent products.

2.3 PLANNING AND ORGANISING OF VERIFICATION

Verification of the thermal design should be planned for each project and form an integral part of the overall product development process. The nature and size of the product development process and available data on previous products influence how the verification should be done.

Thermal control solutions have a major impact on e.g. the mechanical design of the electronic equipment and component selection. Therefore *the first reviews* should be scheduled already for the early *idea search and product definition phase* and the early design phase. In these early reviews the general impact of the thermal design on the product and product development are defined. It is of primary importance to define the organisation of the thermal design and the reviews that will be held to discuss the results of the thermal design and its influences on the product. At the same time the goals, quality and contents of the thermal design are set and preliminary plans are made for tests and tests measurements to verify the thermal design.

Below is a list (table) of topics that should be checked in the design review. These make up *the contents of verification* and the methods of verification. According to the development phase different topics are handled with different priorities in the respective design reviews.

The *nature of verification* must be kept in mind — whether it is the verification of a simple printed circuit board (PCB) or a system with several electronics units. A sketch is made of how the verification should be made in each case, the level of accuracy of the verification is specified, the types or measurements and tests are defined, and the persons who will verify the design are selected.

Previous design and test data on similar products are sought.. The usability of such information in verifying the design of a new product is ascertained. The level of costs of verification and level of risk incurred by releasing the product for manufacture are defined.

The role of the verification engineer does not include the design of the product. The designer is responsible for the design process and its results and also for organising the design work. The verification engineer helps the progress of the design work towards meeting its goals.

General contents of the verification process

1	Definition of the object of verification
	Focus is put on that part of product development on which the verification activity is performed. This topic is studied in detail and the general goals set for it are clarified. Both the product designers and design verification personnel must become sufficiently familiar with the whole product to be able to limit the contents of the verification activity such that its size is appropriate to the project and that it is focused on important technical targets.

2	Timeline for design reviews
	The verification of thermal design starts at the idea-generating and sketching phases of the product design project, where the goals are set for the development work. In the initial phase the goals for the thermal design are defined; here it is productive to start the planning of verification activities and scheduling. The thermal design reviews are scheduled close to important decision timelines, such as goal definition, selection of components and materials, selection of design principles, selection of design tools, model sketching, evaluation of simulation results, assessment of measurements and tests, evaluation of the final design, and planning of field information collection. It is of primary importance to schedule the design reviews in the early phases, so that the different engineering sectors involved in the product design can best take into account the decisions made by the other sectors.

3 Organisation

The design team is assembled. Those taking part in verification of the thermal design are selected. Participants of the reviews in different phases of design must include the project manager, the thermal control lead engineer, the quality manager responsibile for thermal control issues, and, if necessary, other designers and quality personnel with responsibilities such as electrical, mechanical, EMC and environmental design.

Also persons making the material and component selection must take part in the relevant reviews. If possible, it is desirable to invite outside experts with enough experience with similar designs in the fields of thermal design, thermal analysis, modelling, and simulation to these reviews.

If the product development is carried out by different organisations of the company or subcontracted, it must be ensured that there is an agreement as to which topics relating to thermal design are shared between the separate organisations, and that these organisations are represented in reviews. It is essential that the product design interfaces of each organisational unit are well defined. The project manager must ensure that these interface definitions overlap to such a degree that no important task falls between the responsibilities of two organisations.

Outlining the design work according to its contents must be settled in the product reviews in the beginning of the design phase, in order to give the designers in different engineering groups a clear picture of their tasks and responsibilities. Functioning of the interfaces of the thermal design must be assured by an adequate number of personal contacts between relevant people to preclude “grey areas” between engineering fields.

4 Reporting

Documentation of the verification results is necessary to ensure the correctness of the design solutions, test results and possible related corrective actions. In addition to the primary subject matter, verification reports should also include problems encountered, their treatment, corrective actions with justification, the results of inspections, tests and analysis after design changes, and the contact information of the personnel who carried out the verification activities.

During the thermal design process it is very useful to keep a log book describing the design details and development of the thermal model. This helps build a database of experimental design information. The notes should also enable other thermal designers to understand the grounds on which certain design decisions have been made. This will help minimise disruption caused by any personnel changes during the thermal design process.

Tests and their measurements must be planned in detail before starting the testing. Especially useful in performing the tests is good planning with documentation that reduces the risk of losing data through mistakes in performing the tests and reduces the need to re-tests. Good planning reduces the amount of work needed in the documentation and analysis of test data. Adequate resources should be invested in the automated handling of measurement data to allow engineers to focus on checking the correctness of the data.

5 Thermal design

At the very least, verification of thermal design includes:

- goals, boundary conditions and design margins for the thermal design
- environmental tolerance, mechanics, EMC, etc.
- reliability target and critical components
- regulatory specifications and company standards
- material and component data (thermal properties, failure mechanisms)
- basic thermal design solutions
- design calculations, computer modelling and simulations (steady state, dynamic)
- consideration of the need for measurements and testing in the design of the product
- design documentation, log book of design, and backup copies of computer files containing project information.

Attention must be paid to the suitability of the chosen analysis methods for solving the task at hand and to the workability of the thermal solutions chosen. Modelling work tries to ensure that the model represents the physical product well enough, including the definition of measurement points. A large portion of the design work consists of working out technical details and selecting materials. Simulations are used to verify the reasonableness of the design and to locate the possible design flaws.

6 Measurements

The measurements produce realistic thermal design information about the product. The quality and quantity of the planned tests are inspected keeping in mind the needs of the particulate product design task. The measurement needs must be recognised already during the thermal design phase. The thermal designer should identify the measurement objectives and make sure that the measurement points are included in possible thermal models to facilitate comparison of simulation results with measurement data.

Verification of measurements should include at least the following checkpoints:

- selection of measurement points and measurable parameters relevant to the thermal design (such as temperature distribution, power, air flow, emissivity of surfaces)
- possible measurements of materials and components
- methods of measurement and the accuracy achievable in proportion to the design requirements
- calibration and suitability of the measurement equipment for the task
- sources of measurement errors (probes, environment)
- consideration of time constants of the measured objects
- collecting, archiving, and documentation of measurement data

Adequate test planning prior to the tests decreases the number and seriousness of errors during testing, and ensures that all needed data are actually recorded. Test execution is simplified by preparing test record sheets in advance.

7 Testing

Testing places the product or its prototype under environmental stresses that correspond to operational and environmental loads. Basic tests can be performed in laboratory conditions while operating the equipment at its nominal and maximum power. Depending on how much information is needed and desired, the equipment is exposed to various extreme conditions that it might encounter under operating conditions. Typical thermal tests include steady state and dynamic thermal balance tests that may include variation of the power level of the equipment from minimum to maximum. It is crucial that these tests verify that the product

- can operate in different environmental extremes,
- does not suffer damage in test environments, and
- performs reliably throughout its design service life.

The stress level of the tests can be raised, e.g. gradually, until the equipment under test fails. This gives the margin between the specified stress (environment) limit and the failure level.

For the sake of thermal design itself, it is essential to check that the thermal parameters (temperatures, power losses, air flow etc.) used in the tests are the same as planned. At the same time the conditions of the test environment must be as specified.

The test measurements should give values of real thermal parameters (temperatures, flow parameters etc.) of the object to see how close these are to the design goals. Mere pass/failure tests may lead to gross misjudgements in the evaluation of performance of the product.

The verification activities include the review of test plans and test results, and assessment of whether the tests were adequate to describe the various environmental stresses likely to act upon the product. Corrective actions due to possible flaws or failures are checked and the need for re-testing is evaluated.

8 Assessment of design- and test data

As the product development project nears completion a final design review should be done to verify the correctness of the results. The review presents in compact form the design results and the prototype or production unit test results, compares them with the goals set for thermal and other design. In a few cases not all the design goals are achieved, partly for technical reasons and partly because of constraints set by the project timetable or funding etc. On the other hand, only production models already delivered to customers can produce relevant information about the behaviour of the product under actual operating conditions. It is worth paying attention to field information, such as repair reports during the warranty period, as this is the only way the designer can get information on how well the design works in real operating conditions and can improve his or her thermal design solutions.

Topics for the final review include

- achievement of the design goals
- possibilities for changes in the goals, taking into account future needs
- functionality of the design solutions for this particular product
- test results and resulting actions
- corrective actions concerning the product and its thermal design
- collection and use of feedback from the field
- recording of product and design ideas concerning possibilities for further improvements

9 The relationship of verification to design goals

Verification usually focuses on checking that the set goals have been met and that well-known design rules have been used. However, it can be made a deeper process whereby the results of the product design are improved, provided it is free to question conventional solutions and actively seek better ways to improve the characteristics of the product.

Re-appraisal of the goals of the product development should be done as the design evolves, paving the way to even better product quality than was originally sought. This should be done jointly with designers in different engineering sectors.

Verification of the goal setting itself is an important part of the product verification. The goal setting must take into account powers, temperatures, mechanics, materials, operation environment, testability and possible use of design mock ups. Also requiring verification in this context are the goals arising from the operating environment, degradation of materials, ergonomics, safety requirements, restrictions on EMC emissions and susceptibility, and other aspects which may affect the thermal design.

To control the component stress levels one must identify the most failure-prone components and the stresses that act upon them, such as over-voltage, temperature cycling, mechanical stresses, moisture, and air pollution, all of which place restrictions and demands on the thermal design.

> Example of risk-prone heat removal techniques is allowing continuous large temperature changes or the use of overly high forced convection which may unintentionally lead to acceleration of various failure mechanisms.

The thermal control system should not decrease the reliability of the equipment. Thus the reliability of the heat transfer components (fans, heat exchangers etc.) must be known as accurately as for the rest of electronic and other components.

3 THERMAL DESIGN

3.1 THE GOALS FOR THERMAL DESIGN

The basic goal of the thermal design of electronic equipment is to plan the thermal balance of the equipment so that it operates reliably within the specified environmental conditions throughout its service life. The environmental conditions include those during manufacture, transport, assembly and operation of the equipment.

According to Figure 4, the main causes of failure of electronic equipment are heat and moisture (humidity). Temperature (high/low) and its variation, as well as moisture and its variation, alter the physical and chemical properties of materials and components. The extent of these effects is decisive if some change of temperature, its absolute level or moisture level has noticeable effects on the properties of the product under design.

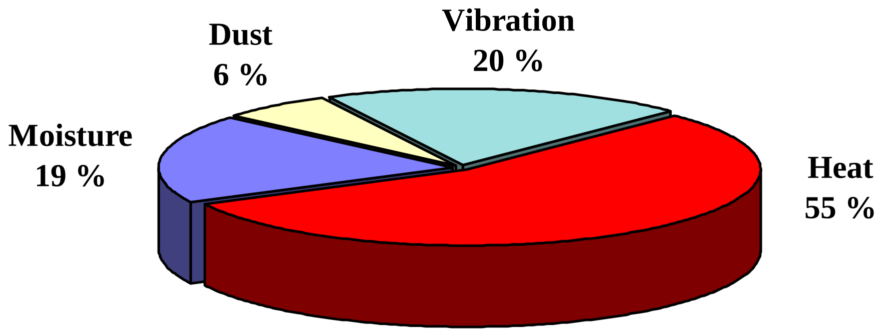


Fig. 4. Principal causes of failure of electronics in Avionics (Flomerics, US Air Avionics Integrity Program).

Thermal design cannot proceed merely from considerations based on thermal properties; rather the designer has to maintain good contact with electrical and mechanical designers to enable control of the total functionality of the equipment. In addition, contacts with designers of electromagnetic compatibility (EMC) are necessary to ensure that the equipment is electromagnetically sufficiently tight, avoiding design solutions that make the equipment a potential source of disturbance or sensitive to external electromagnetic interferences.

Thermal design eliminates problems caused by overheating, maintains a correct and adequately uniform operating temperature distribution inside the equipment box, influences the performance of the unit in various demanding environments and, for example, reduces the harmful effects of moisture.

It is productive in the planning of thermal design to estimate how detailed a design should be, and to seek information on the design of similar equipment or parts of equipment. Thermal design can be assisted by modelling, but this is not necessary where the thermal design can be done experimentally and verified by visual inspections, measurements and thermal tests.

Basic topics in the goal setting for thermal design include:

- a survey of existing thermal problems
- the effect of other than thermal design objectives on thermal design
- gathering of existing thermal design data on the electronic equipment
- definition of coarse design goals
- usage of physical structural and thermal models (prototypes) in the design work
- a description of the level of detail and accuracy of available simulation models
- the need to divide the simulation model into sub-models using appropriate interfaces
- the selection of modelling tools, if really needed
- collection of information concerning components and materials
- definition of design margins for the equipment and component levels
- collection of information on the most critical failure mechanisms of the used components and materials
- selection of tests and measurement methods to be used in the verification.

These basic choices assure that the goals set, the modelling type, the design accuracy, and the test and measurement methods work together so that unintentional over- or under design is avoided and that excessively expensive modelling and/or lengthy testing are avoided.

Gathering information about the most critical failure mechanisms of the intended components and materials is necessary to ensure that the main activities related to the thermal design focus on details where possible failures affect primarily the usability and reliability of the equipment.

3.2 THE PHYSICAL BASIS OF THERMAL DESIGN

The basic goal of thermal design is to keep the temperatures of parts and components inside the equipment within the limits set by their specifications, to level internal temperature differences, and to lead excessive waste heat away from the equipment in a technically and economically sensible way. Prevention of excessive cooling of internal parts of the equipment in outdoor conditions is often a part of the thermal design.

Thermal design is based on the understanding of heat transfer processes (Fig. 5). The available paths for heat transfer are conduction, convection and radiation. Flow and phase changes of a fluid (gas, liquid) can increase heat transfer significantly. Detailed information concerning these is given in Appendix 1 "Fundamentals of heat transfer", which treats thermal design from component to unit level and describes the basic laws and models of mass and heat transfer and fluid dynamics.

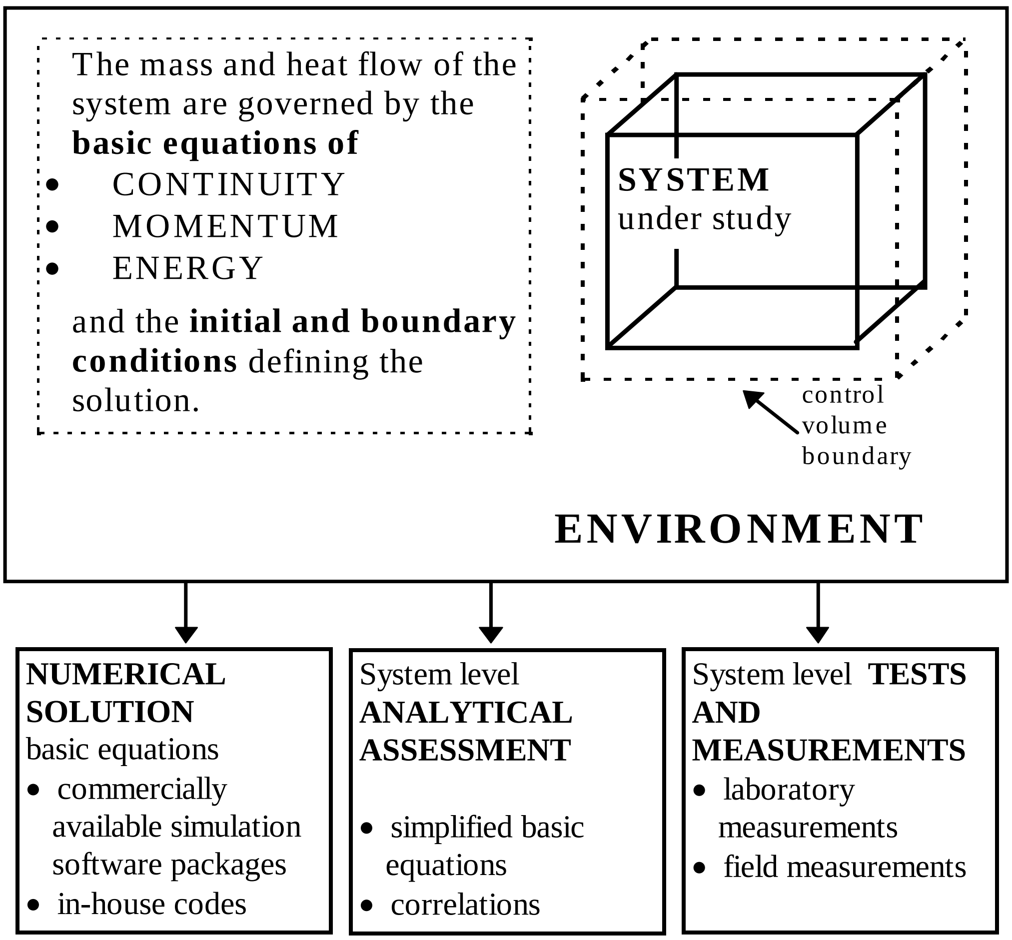


Figure 5. The physical basis of thermal design (Appendix 1).

In verification of the physical basis of heat transfer, focus is on utilising the different modes of heat transfer — conduction, convection and radiation — in the thermal control of the product. This includes assessment of the mechanisms that can be used in each design detail, for example whether there is an option of using fluid (liquid or gaseous medium) or phase transfer (e.g. heat pipe) for cooling. These appraisals are closely related to the possibilities of applying different materials, structural designs, heat exchangers, fans etc. in the search for new kinds of physical solutions.

In this context assessment is made of the suitability of the physical models and equations, and of the calculation methods for analysing this specific problem. This level of verification delves into the basics of thermal design and should be done when the company is selecting the methods, tools and designers for the thermal design. The designer must understand the physical limitations of different tools and methods to avoid unnecessary and faulty analysis calculations. Various thermal analysis software packages contain sources of error in their calculation routines that are not easily known to the designer. Therefore the verification must try to evaluate the calculated results by comparing them with measured values, so that mistakes in analysis and calculation errors do not lead to the wrong conclusions.

> An example of such a problem is the difficulty of solving the frequently met case of air flow around a printed circuit board, which with its components has a very complex contour, leading to transitions from laminar flow to turbulent. This creates the difficulty of finding analytical solutions for the air flow velocity and temperature distribution near the printed circuit boards, affecting the estimation of efficiency of the convective heat transfer. The problem of measuring these parameters is even more complex.
>
> Another example of a physical phenomenon that is hard to model is the conduction of heat across the interface of two joined parts. The thermal conduction is influenced greatly by the surface roughness, planarity, and contact pressure of the mating surfaces. During a long service life corrosion of the mating surfaces or degradation of the medium (e.g. silicon grease) used to improve conduction can increase the thermal resistance of the joint. Similar problems exist in the control of the emission and absorption coefficients of different materials.

In Figure 5 the system to be analysed is bounded by a control volume describing the conservation of mass, momentum and energy, as well as the continuity of heat transfer. In the thermal design process the equipment being designed is divided into parts or elements each having a well-defined thermal behaviour. It is essential that the parts mounted in series or parallel are divided in a physically meaningful way so that the thermal parameters on both sides of their interfaces are well defined.

Components, printed circuit boards and cabinets (box) are examples of such a natural division. To calculate the internal temperatures of a component, e.g. the junction temperatures of a semiconductor device, the designer needs to have information about the component's internal structure and environment. The environment comprises the printed circuit board, possible heat sink and air flowing past the component, and hot areas in the vicinity that radiate heat. An adequately detailed analysis of the printed circuit board (with its components) is required to understand the thermal behaviour of the PCB. The printed circuit board is surrounded by other boards, the box walls, and the fluid (air) and is influenced by its connectors and support structures. Knowledge of the interior of the equipment facilitates understanding of the thermal behaviour of the equipment at system level, and how this is influenced by the environment.

3.3 DOCUMENTATION OF THERMAL DESIGN

Documentation of all parts of the task — such as limit values used, assumptions and simplifications made — is necessary in thermal design as in other fields of engineering design, and should be done simultaneously with the execution of (sub-)tasks. This immediate documentation removes the inaccuracies caused by relying on one´s memory and fulfils the primary goal of documentation — traceability of the design process — more efficiently.

The need for written reporting becomes increasingly important the longer the duration of the project. The documentation must cover the whole chain of thermal design from the sketching of ideas to the final design specification. In this chain the log (journal) of engineering changes, which records accurately the design changes made, their grounds (changes in electrical or mechanical design, etc.), and the justification for design improvements, is essential. If the thermal design is subcontracted outside the company this document must state who requested the design changes, and the possible influence of these changes on meeting the project's goals, timetable and cost. Otherwise later on it may prove extremely difficult to trace the history of the development.

Thermal design is not an isolated part of product design. It is one important part of the concurrent design process and the thermal designer must work in especially close co-operation with electronics and mechanical designers.

When everything affects everything else, these people must find a good compromise in order to reach the design objectives. The documentation created by the thermal designer is not meant to be buried away in files, but to be distributed and especially to be read by all whose work it affects. The effective distribution of this information assures that all engineers in the project keep up to date at all phases and that any problems are quickly resolved.

Good documentation of the thermal design is also an invaluable help in the planning of future projects. With the help of the database(s) of past projects it is possible to estimate the amount of work and cost of design and testing quite accurately. Moreover, good design solutions from the past can often be applied with only minor changes to new, different applications. The materials files and modelling practices gathered in past analyses also expedite the design process.

Information networks and the service provided by them are improving rapidly, facilitating distribution of the documentation and transferral of data. A well-planned and functioning information network gives fast and easy access to the latest correct information.

The European Space Agency (ESA) recently carried out a study (SME-NET) on the effectiveness of a "virtual company" operating from three different countries over the Internet. The project was a collaborative effort between VTT (Finland), ORS (Austria) and HTS AG (Switzerland). The recent experience suggests that such arrangement works well in all aspects of product design and that it does decrease costs and improve the efficiency of project work.

3.4 PROBLEM DEFINITION AND BOUNDARY CONDITIONS

When performing thermal design it must be understood that the design is done not only for its own sake, but typically because there is a need, for example, to improve the reliability of the equipment or its range of operational environments. It is important to clarify the purpose of the thermal design early in the project. Is the goal to verify the thermal behaviour of an existing equipment design under extreme conditions (power, temperature), or to optimise the internal heat transfer paths of an equipment design, or is a solution sought that minimises the need for forced convection? There is an infinite number of angles from which to view the problem! The chosen goals strongly influence the amount and type of work needed to perform the thermal design.

Once the goals have been set, and when the problem at hand requires the creation of a mathematical model using a specific software code, all the *boundary conditions* influencing the thermal design must be defined. They are:

1. Mechanical constraints
   - the equipment dimensions have been set
   - the materials have been chosen
   - surface treatments of the materials have been decided
2. Electrical constants
   - the power of the unit is fixed (maximum, minimum and average)
   - the component layout has been fixed
   - the PCB mounting layout has been fixed
   - electromagnetic requirements for the packaging have been determined
3. Thermal characteristics of components and materials
   - maximum allowable operating temperatures of components
   - reliability target of the unit
   - temperature dependence of the thermal and other properties of the materials
4. Environment
   - temperature limits of the operating environment
   - sources of heat in the environment (heaters, the Sun)
   - thermal sinks (mounting platform, ventilation, rain, wind)
   - requirements set by the corrosion protection
   - requirements set by the different individual installations
5. Special requirements by the customer or marketing department
   - no fans
   - no heaters
   - ergonomics, acoustical noise, appearance...

Once all boundary conditions have been defined based on the product specification, the analysis cases and results sought must be clearly defined. Typically the analysis cases include the hottest possible case (highest power level, largest heat input from the environment and highest ambient temperature etc.) and coldest possible case. A case that strongly affects the reliability of the unit is one that includes large power level changes or wide fluctuations of environmental temperature, leading to cyclic temperature changes that stress all interfaces and materials. Easing these circumstances by thermal design may be basis of the thermal design process.

Often, problems that arise in interpretating the results of thermal design analysis derive from the fact that the analysis performed does not meet the goals set for it, because the parties involved differed concerning what was supposed to be performed and for what reason.

Careful planning of the contents of the analysis cases, their boundary conditions and impact of simplifications of the model and documenting analysis work, thoroughly ensures that the customer (whether from the same company or an external client) gets what he/she wants!

3.5 DESIGN TASK

Thermal design can be performed at various levels of detail and during several phases of the product development process. The earlier these questions arise the better the solutions that can be found. Typical levels of thermal design are:

1. Pre-design
   - the total product is in a preliminary sketching phase
   - there are no comparisons or models for the particular product being designed
   - thermal boundary conditions are usually not well defined
   - there is no clear picture of the dimensions and the materials to be used
   - the design is based on intuitive general-level thinking
   - this stage has a significant influence on the results of later phases of the design
2. Product design
   - the product design has a concrete content
   - the design is based on modelling and/or test measurements of an existing product geometry
   - thermal boundary conditions, materials and interfaces are known
   - there are no radical changes from existing solutions
   - the result is based on good pre-design
3. Follow-up
   - occurs when the product design is ready and some checks are desired while prototype production is in progress at the factory
   - is based on measurement records or results of simulations
   - consists mainly of analysis of different operational modes and special situations

- includes damage control and prediction
- offers minimal opportunity for design changes.

At all these levels the thermal design is a rational iterative process (even though the after-sales information and conclusions based on it do not necessarily influence the product generation that the information concerns) including the following phases:

1. Survey of problems
   - for example, survey of the operating or survival temperature limits of the components intended to be used in the design
   - charting of the thermal endurance of the used components
   - charting of the external requirements for the product
2. Preliminary analysis
   - can be performed at several levels depending on the required accuracy and level of detail
   - can be based on experience of earlier similar design cases
   - if the design is done with thoroughness and accurately enough using the right tools, the areas needing correction can be identified.
3. Solution proposals
   - require comments from the electrical and mechanical designers
   - include proposals for alternatives
   - must be based on the best possible utilisation and appropriateness of all possible heat transfer mechanisms
4. Updated analysis
   - comparison of the analysis and analysis results of the proposed solutions
   - selection of the most suitable working principle
   - final freezing of the design of a product or product generation.

In performing iterations of analysis calculations and reviewing the results, special attention must be directed to how well the requirements and boundary conditions (described in the previous chapter) were fulfilled. The analyst must keep a careful log of his actions. What simplifications were made? What were their effects? How well did each model meet the requirements and boundary conditions set for it during the definition phase? Careful documentation of the analysis phase is invaluable in the planning of possible (and desirable) measurement of the thermal behaviour and physical parameters of the product.

The final results of the thermal design are often not the best possible because of the numerous limiting boundary conditions imposed by electrical and mechanical design, but with good co-operation among the design team members the solution may be the best for the situation at hand. For later product development the thermal design documentation must include the reasoning that led to a particular design. This experience can improve design work in its early phase by guiding the design in a direction with the greatest promise of success.

3.6 PRESENTATION OF DESIGN RESULTS

Once the design task has been carefully defined and the goals have been set for the thermal design, the results of the design and analysis work can be presented in relation to these requirements. The results are a condensed presentation of the thermal design. Particular attention must be paid to the presentation format.

1. Present all analysis/measurement cases
2. Present the boundary conditions of all cases
    - environmental conditions
    - power, etc.
3. Present the results in a compact way
    - Use a table that presents the temperatures corresponding to the analysis cases required by the task definition, other temperatures of special interest and the calculated design margins.
    - Use charts for describing the effects of changing parameters.
    - State the accuracy of the results.
4. Present the synthesis based on the results
    - How good is the design?
    - How well does the design meet the goals set in the problem statement? (This is an important topic and must be pressed.)
    - Possible proposals for engineering changes to improve the design can be presented in a separate chapter.

Often the summary and the chapter on analysis results in the thermal design documentation are the only ones of interest to readers other than thermal design engineers. Thus the language in these chapters must be as concise, efficient, and clear as possible.

4 THERMAL MODELLING

4.1 MODELLING ACCURACY

When the product design requires thermal design to be performed, the first step is to define the required accuracy of the results of the thermal design. Analysis can vary from “fast-and-dirty” calculations based on general assumptions to highly detailed numerical simulations. Numerical simulation takes into account all possible methods and paths of heat transfer with high accuracy, and the thermal modelling task can with all its iterations take up to several years to perform.

The long duration of thermal analysis work is not caused as much by the problems of modelling and/or shortage of computer resources as by changes of product geometry during the long development process and by the increasingly detailed definition of material and heat transfer parameters during the process. The overall thermal design problem and its goals may change during the process because of changes in other design areas.

Next the thermal designer must select the geometric accuracy of the thermal model representing the hardware, and which methods of heat transfer will be taken into account in the thermal analysis. The selection of geometric accuracy and heat transfer modes must be compatible and support each other in order to meet the requirements set for the thermal design problem.

4.2 QUALITY OF THE THERMAL MODEL

The examination of quality of the thermal model is one of several thermal design verification activities. The modelling part of thermal design starts with analysis leading to modelling and simulation. Measurements and tests are finally used to verify the results of the design.

The quality of the model can be inspected by comparing the temperature distributions of the model and test measurements and/or by making a detailed analysis of all the heat transfer paths and modes of the structure or system being analysed, using as reference the best know-how and information on the modes of heat transfer and thermal design.

If the verification uses only the comparison of temperature distributions of the model with the results of measurements, the wrong thermal model may be accepted. This may happen if the thermal model is deliberately constructed merely to produce a matching temperature distribution, but does not correctly describe heat flows inside and out of the equipment box.

> An example of such a situation is a multi-board electronic cabinet, where the temperatures of the walls in the model may be identical to the measurements only if the thermal conduction from printed wiring boards through the fittings to the walls of the cabinet is matched. In reality the most effective heat transfer mode may be radiation from the printed circuit boards.

An incorrect thermal model, where not all heat transfer modes are analysed, may give a correct result over a very small range of parameter changes, but does not offer solutions to thermal problems that can only be solved with a good and correct thermal model. The reliability of such a wrong model is poor. If an incorrect or over-simple model has been accepted, there is a danger of causing failures or even fully destroying the equipment. This is because in certain conditions the thermal behaviour of the real equipment differs too much from the hypotheses made during design.

The measurements can be faulty as well. For this reason it is good practice to check which is more reliable: the model results or the test results. A combination wherein a model modified to match faulty test measurement data is used to predict the thermal behaviour of equipment in all kinds of ambient conditions is a fatal one in the current competitive markets of electronic equipment.

When using modern modelling and analysis tools together with careful modelling techniques (all generalisations and simplifications are justified) possibly the fastest and best way to analyse the thermal model is to compare the thermal distribution given by the model with the measurement results.

Perhaps the most important part of thermal modelling is keeping a detailed record of all activities during creation of the model, such as a comprehensive documentation of thermal parameters, assumptions, and simplifications, their possible effects, and the grounds for their use (see paragraphs 3.3, 3.4 and 3.6).

4.3 PROBLEMS IN MODELLING

A thermal model simulates mathematically the thermal behaviour of electronic equipment in specific situations where the internal and external thermal conditions for the unit vary. This kind of model can be quite simple, dealing only with average thermal parameters such as air temperature, pressure, flow velocity and overall heat power. On the other hand the model can be very complicated and full of details ranging from modelled components, printed circuit boards and board edge guides to the system level.

A very detailed model can predict, for example, the natural convection from the outer surfaces of the electronic equipment cabinet and the radiative heat transfer between component boards and even the conduction of heat in a transistor or a microprocessor along its leads. In a typical thermal model this kind of detail concerning the heat transfer paths and methods can in most cases be omitted with justification. In order to understand how important the effects are of simplifying the modelling of the heat transfer path, the designer should understand the magnitude of these effects on the heat transfer itself.

One of the most challenging aspects of thermal modelling is to identify potential problem areas in all kinds of environmental and operational situations, and to understand the methods of heat transfer in such situations in order to increase the geometric accuracy and accuracy of the calculated heat transfer in the right places and in the right way.

Often the places where increased model accuracy is required are not known initially but emerge during the first analysis runs if the modelling work is done carefully. The accuracy of the most important parts of the model can be improved by modifying the model iteratively. This entails not only better geometric accuracy but also taking into account all modes of heat transfer.

Radiative heat transfer between the internal surfaces of the equipment box is often omitted under the impression that only convection is meaningful. In modelling convection one must take into account that the air flow pattern can change drastically over a short distance. Laminar flow can change abruptly to strongly turbulent, with a dramatic impact on the convective heat transfer coefficient of adjacent areas Such local variations in heat transfer coefficients make modelling work difficult. The accuracy and level of detail of the thermal model determines the quality and usefulness of the results.

In the early phase of modelling, the designer must direct his or her attention to assessing how realistic the results are, since no comparative information from measurements is yet available to support the calculated results. This is not easy and requires both experience and good knowledge of the model, as well as understanding the physical phenomena on which the model is based. A simple model-checking routine can easily increase the reliability of the analysis results. The following should be checked:

1. Heat transfer paths must be continuous

   Check those areas where “cold” and “hot” regions are close to each other without any apparent influence on each other.

2. Thermal balance

   In thermal equilibrium, the sum of the power generated in the system and the power absorbed by the system or otherwise received by it must equal the power expelled by the system into its environment.

Once all planned simulations have been performed and the results compared with measured values, it is often hard to find nodes in the model that correspond to measurement points which should have the same temperatures or other parameters being compared. In the modelling work the designer must also draw up a plan of the locations of test measurements. Often the model is a compromise at some level —with respect either to the geometric accuracy or to insufficient thermal parameters — that may lead to considerable differences between the model results and the corresponding measurements. These differences may be further widened by flaws and generalisations in the modelling technique. The analyst may, for example, use computer software or a thermal network or mesh geometry not best suited to the problem at hand, possibly creating unsatisfactory results.

4.4 DESIGN GOALS AND MODELLING

As stated above, optimisation of the model accuracy is one of the most demanding tasks in thermal design. Optimisation is greatly influenced by the goals set by the product design for the behaviour and operational environments of the equipment. These goals determine the heat output, external conditions, and temperature limits for the operational and storage conditions of the equipment. Once the check points in the model (e.g. temperatures of critical components, boards, air, etc.) and the environmental boundary conditions are well defined, optimisation of the modelling tools and accuracy of the results is almost automatic. It is important to define the purpose of the analysis. Is it to optimise the solution so that it is the most appropriate and efficient for the whole or part of the unit, or is it merely a calculation to check that the given specifications have been met? The fundamental difference between these two makes the modelling quite different.

4.5 CHOOSING MODELLING SOFTWARE

The complexity of the object being modelled and the purpose of the modelling prescribe to a large extent the selection of modelling tools. For the simplest cases an electronic calculator and a few basic heat transfer equations are adequate. As the problems and geometry get more complex, the analysis tools become more elaborate and powerful.

> An example of thermal analysis software packages used in 1997 to solve heat transfer problems in a specialised field is SAUNA. This American computer program tackles complex heat transfer problems involving printed circuit boards and simple mechanical structures. The best software tools are various numerical programs that solve simultaneously for time conduction, flow field and radiation (e.g. I-DEAS ESC, I-DEAS TMG and Flotherm).

Whatever tool is used, the prerequisite for successful thermal design is a through understanding of heat transfer phenomena and ways to change the relative magnitudes of heat transfer modes in each case, thus guiding the thermal behaviour of the equipment in the desired direction. It is good to understand that the largest source of error in thermal design — as in the case of any modelling and simulation — is the person who performs the design work, no matter how advanced the technologies being utilised. Even the best software produces only as accurate results as it is requested to do.

4.6 PHYSICAL PROPERTIES

The generation of a thermal mathematical model requires knowledge of large amount of input data:

- mechanical structure of the analysis object
- thermal properties of materials and components
- the surface treatments used or anticipated to be used
- environmental data
- system overall power level and its distribution
- effects caused by the ageing of materials.

The parameter groups defining extreme analysis cases (and often also a case simulating the typical operational condition), such as the hottest and the coldest case, are drawn from this group of basic information according to the requirements.

4.7 PRINCIPLES OF THERMAL MODELLING

The basic goal is to improve reliability (cool electronics)

Several studies show that the failure rates and causes of failure of electronic equipment are related to its operational temperature (Fig. 4, page 21). Thermal modelling helps to find means that allow the thermal behaviour of the electronic equipment to stay within the specified ranges at extreme limits of the environmental parameters without the building and testing of expensive prototypes. One of the leading ideas behind the planning and creation of the thermal model is to use it to find solutions to thermal problems related to those structures and electronic components that are most critical to the design and of most interest to the designers of the product.

Clarification of the goals of modelling

In defining the goals and tasks for the thermal modelling one must keep in mind what the purpose of the modelling is. This is equally important whether the thermal analysis is done in-house or subcontracted. These goals must be documented in detail so that planning of the modelling work is in the right direction from the outset. Later, possible changes in the goals may influence the nature of the modelling work fundamentally and may require a great deal of re-work thus increasing the cost.

> For example, if the operation of the equipment requires the surface temperature of a microprocessor to be below a certain limit, the model must be constructed so that the best accuracy is achieved in this particular area and those modes of heat transfer that have the greatest influence on the temperature of this component are modelled accurately. Simultaneously one must make sure that the accuracy at the system level is adequate, so that the whole model is reliable. Different targets and objects can modify the model in different directions.

Sensitivity analysis

As mentioned earlier, the same thermal model is used for analysis at different extreme conditions by changing the power levels, environmental boundary conditions and the thermal characteristics of the structure. All analysis cases must be well documented so that one can determine which changes in the model cause which changes in thermal behaviour.

In fine tuning the model to match the measurement data one should limit the changes to only one or two parameters at a time in order to see clearly the effects of changing different parameters.

One of the most often used and most important design criteria for a thermally good structure or system is its insensitivity to changes of individual thermal parameters. A good practice is always to perform a **sensitivity analysis** for the thermal model, changing various parameters one by one and recording the subsequent changes of temperature at points of interest. Then the stability of the system being analysed and the inaccuracy caused by incorrect thermal model parameters can be determined, increasing the model reliability. The inaccuracy of the model results — for a good model — decreases as the analysis work proceeds starting from ±10°C and finally getting up to ±3°C.

Use of thermal tests

When designing the thermal model, usually only some presumptions and listed information are available at the time concerning the behaviour of the thermal interfaces of structures. Various contact surfaces produce special problems. The heat transfer coefficients of such contact surfaces varies widely (100...5000 W/m^2K) depending on the contact type and possible use of heat conductive intermediate materials. Only thermal tests (cf. chapter 6) can give an accurate description of how heat flows and what the real values of heat transfer coefficients are over the contact surfaces.

Using these test results, final fine-tuning of the thermal model can be done to reach the real condition. The situation is optimal if the tests are performed using several changing environmental conditions (various temperatures of environment, power levels of equipment, positions of the structure etc.) also simulated using the model. In this way the method designer can avoid statistical fluctuations and identify differences between the behaviour of the equipment and that of the model. Also possible causes for these differences can be pinpointed using this method.

The designer should exert caution when comparing the results of tests and the thermal model, as test conditions are rarely the same as the interface parameters to the environment used in the model. In such cases, after careful study of the test conditions and parameters used, the thermal model of the system is modified to better describe the test conditions. This thermal model simulating the thermal tests (so-called **test model)** is compared with the measurement results. It should be noted that the original thermal model is not compared with the test results at this stage. The **test model** is then corrected to better fit the measurement data. Once the test model produces the correct results, the modifications to the test model are transferred to the **original thermal model** and the relevant thermal analysis cases are re-solved. To avoid mistakes and design iterations the test plan must be drawn up thoroughly and documented together with the measurement data. The measurement points chosen in the planning of the tests must be simply relatable to the thermal model.

4.8 THERMAL INTERFACES

Modelling of heat transfer mechanisms

The efficiency and quality of heat transfer depend very strongly on the characteristics of the thermal interfaces. One of the most important tasks in model verification is checking the heat transfer mechanisms (convection, radiation and conduction) at each interface and their proportional shares in the transfer of total waste heat. For example, one can verify whether the assumptions made for a particulate surface concerning the relative importance of heat transfer by convection and radiation are correct. One can also check whether it is possible to model the radiative heat transfer using the thermo-optical parameter values available in different information sources, or whether modifications are necessary e.g. to take into account the complex surface structure that could not be modelled in detail.

Thermal interfaces can be divided into two classes, internal and external. External interfaces transfer heat to the environment (and vice versa). Thus the characteristics and means of heat transfer at those surfaces determine the average temperature difference between the unit and its environment. Internal interfaces define the heat transfer paths inside the equipment box. Large internal temperature differences can be a sign of poor design of internal heat transfer paths.

External interfaces

In the verification process the thermal designer checks which external thermal interfaces have been incorporated in the thermal model, what are the modelled heat transfer mechanisms at those interfaces and how they have been modelled. One must also be able to estimate the heat transfer capacity of these surfaces and to compare the estimated capacity with the measurement data. An important research topic is the assessment of the influence of changes of external environmental parameters at these interfaces. These changes include the effects of corrosion, dirt, radiation, ageing and other changes caused by the environment to the thermal properties of the interfaces.

It is very important to note that the definition of an external thermal interface does not necessarily refer to the physical location of such a surface in relation to the environment.

> For example, in an equipment cabinet is cooled by ventilation all surfaces in the cabinet that remove heat by convection to the environment are by definition external interfaces. At the same time these surfaces are also internal interfaces because they level the temperature differences inside the equipment cabinet by radiative heat transfer and convection.

Internal interfaces

Internal interfaces guide the internal heat flow and thus level temperature differences. Finally, individual heat transfer paths remove heat from the unit through its external interfaces. The conditions and behaviour of internal interfaces in the model must be checked the same way as for external interfaces. Taking into account, modelling and defining the behaviour of multiple heat-conducting joints makes the verification activity (and modelling) quite demanding and complicated. In these activities the right interpretation of measurement data is emphasised.

In the worst case it is possible to get a correct temperature distribution using a model that has completely wrong heat transfer paths because of poor definition of interfaces. Typically such a model produces correct results only in one analysis case/condition (see the above description of fitting several analysis cases, chapter 4.2). Accepting this kind of model is likely to lead to undesired thermal behaviour and, in the worst case, to destruction of the unit when operating under different conditions.

The knowledge of heat transfer across internal interfaces is very important in creating a working and dependable thermal model. This know-how can be achieved through experience and training, through well performed and documented measurements and by collecting and utilising material information on heat transfer from the best sources available. Good documentation and exchange of information is vital to making high quality thermal models.

If the power distribution of the equipment is uniform and the internal heat transfer paths are well designed, the temperature distribution of the equipment is also uniform. In such a case it is easy to concentrate the design effort to the transfer of heat from the equipment to its environment. This also allows a larger power density for the equipment and a larger range of limiting ambient temperatures that the equipment can sustain with the same design. This creates savings in costs and a marketing advantage over competitors who have to supply a different product for each new application.

> For example, the heat transfer can be greatly increased by improving the mounting of the printed circuit board to its card cage and by improving the mounting of the card cage to the equipment housing. These relatively simple measures can make it possible to increase the power density of the printed circuit board and still prevent an exessive rise of its temperature.

5 COMPONENT LEVEL VERIFICATION

5.1 COMPONENTS IN THERMAL DESIGN

Control of the temperatures of components is necessary to limit the effects of their failure mechanisms. These failure mechanisms build up because of the effects of temperature and heat on the properties of, and interfaces between, the materials. Typically all electrical properties of microcircuits are more or less dependent on temperature. Similarly various long-term changes in materials are accelerated when the temperature rises. Such phenomena include e.g. the diffusion of impurities in the p-n junctions of semiconductors and degradation of contacts and isolations. Especially problematic are the interfaces between different materials such as silicon, metals and plastics, where the first failures usually build up. Often problems arise from widely varying thermal expansion coefficients of materials, both inside the components as well as in other parts of the equipment (Fig. 6). Similarly high relative humidity of the air (> 50% RH) and moisture condensation on surfaces accelerate the corrosion of metals and degrade the electrical insulation between conductors because moist insulators have better conductivity than dry ones. Nonetheless, it is possible to affect these phenomena by appropriate thermal design at the component, unit, and equipment levels.

With fast rising demand for electronics design on an ever diminishing scale with ever increasing power, detailed knowledge of the thermal behaviour of components is crucial. It is increasingly important to model components more accurately than in current practice, where the average power distribution at circuit board level is used to deduce the component and circuit board temperatures. The modelling and characterisation of individual components and optimisation of the circuit board structure and component configuration is a very hard and complicated task if not downright impossible.

Verification of the thermal behaviour of electronic components is in principle simple with modern modelling tools, far more so than the measurements of sufficient accuracy and extent that would be required for proper verification, even though that level is seldom attained.

Two major causes of problems are encountered in thermal modelling: First, there is no available accurate data on the internal structure of the components nor on the materials used. Therefore that part of the component whose temperature is of interest — namely the silicon chip deeply imbedded between different material layers, does not behave in reality as the model predicts. This could be decisive if the whole system is trimmed to work near the extremes of its temperature range. The use of average material properties in such cases can be dangerous. For example, in measurements made by the Technical Research Centre of Finland deviations of as much as 15°C from the model results have been observed for the active component layers.

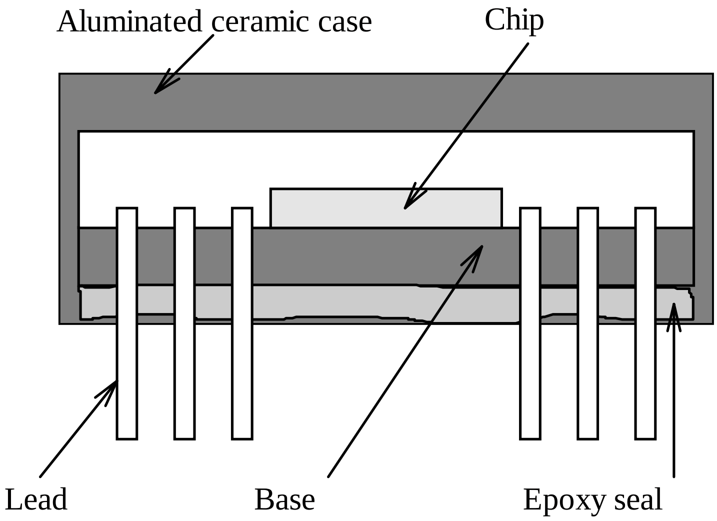


Figure 6. Cross-section of a metallized ceramic case with its silicon chip /5.1/.

5.2 MODELLING OF COMPONENTS

Components can be accurately modelled with modern tools if their structures and materials are known. Often this knowledge is classified or otherwise inaccessible to the thermal designer. A conceptual drawing and general description of materials used are available for most components (Figures 6 and 7). Generally the thermal conductivity of the materials is available from public literature. Good results in thermal design can be achieved only through co-operation with the manufacturer of the component.

Using these data a mathematical model of the component can be created. However, inclusion of such a detailed model into a larger system level model is rarely meaningful and often impossible. The purpose of a detailed model is to be a reference model for the thermal behaviour of the component. The simplified models used in large system level models are compared with this reference model. However, the correctness of the detailed model must be well verified with measurements under controlled test conditions.

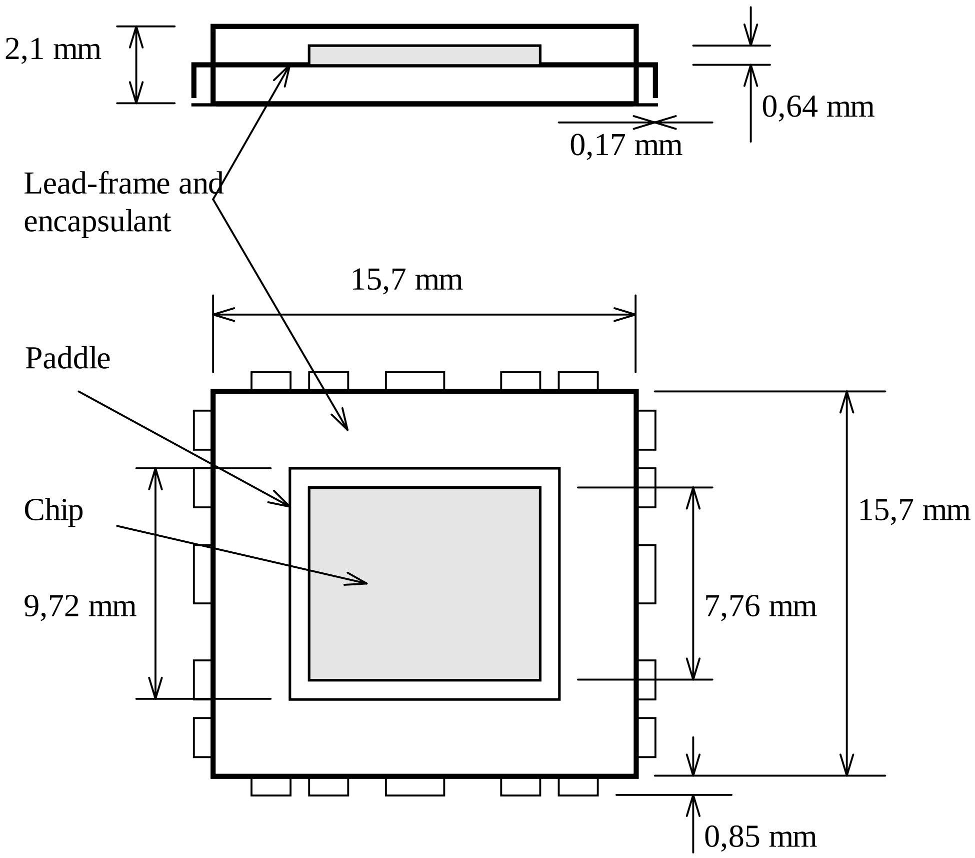


Figure 7. Example of component package geometry and dimensions in an accurate and detailed model. Leads are described as five blocks on each side. The PQFP package is quadratic /5.2/.

There are several types of simplified models depending on what modelling environment (software) is used. The grand European cooperative project DELPHI (Development of Libraries of Physical models for an Integrated design environment) /5.3/ is an example of an attempt having been made to share the responsibility for thermal design between the supplier of the components and the end user. The objectives of the project were:

1. To create a standardised test method for determination of the thermal conductance of different component parts and their relations.
2. To define the quantities needed in thermal design and modelling.

3. To create a foundation for the use of these quantities with the help of measurements and detailed modelling.
4. To develop a thermal resistance model consisting of about seven nodes for each component type. The component supplier must deliver this model and the model must work with sufficient accuracy (< 10 % deviation) in all expected (stated in advance) boundary conditions.

Even though such a simplified thermal resistance DELPHI model is not compatible with all modelling software, the unified and complete presentation format of more accurate and better thermal parameter data is a very good objective. Hopefully this will be realised in practice.

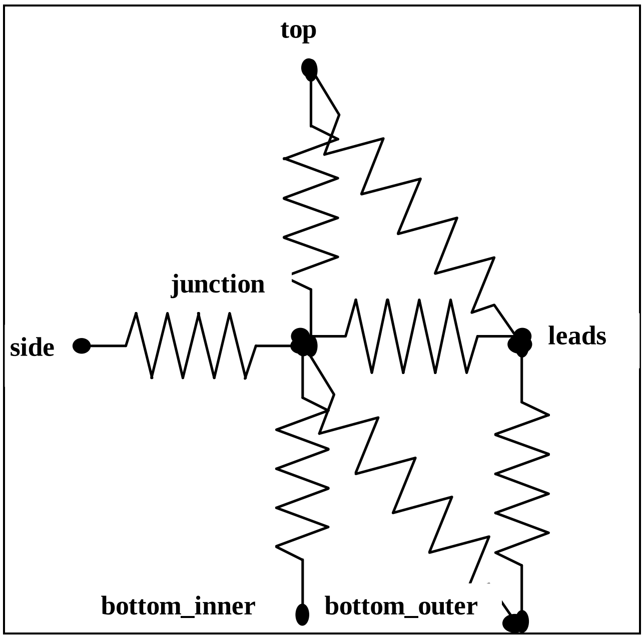


Figure 8. A thermal resistance model of CDIP package /5.4, Fig 1b/. (CDIP = Ceramic Dual Inline Package).

If the modelling tool gives the opportunity to use a structurally compatible (for external dimensions) simplified model of a component, which is more accurate than a simplified thermal resistance node model, then a reliable picture of the thermal behaviour of individual components can be obtained without excessive growth of the model and calculation time. In addition, these models presume a fairly good insight into the component structure and good knowledge of the materials used.

The thermal conductance and thermal capacity data of semiconductor materials, ceramics, plastics and metals used in component structures is fairly readily available (Table 1 includes the material data of Figure 7), and the material parameters within the groups do not vary sufficiently to jeopardise good and reliable analysis, even though a simplified model for the structure is used in the modelling, as well as average parameters for the materials. However, the quality of data is not always good, therefore the designer has to inspect and compare data from different sources and act in light of his or her own experience.

Table 1. Typical parameters used in accurate modelling (Fig. 7) of integrated circuits /5.2/.

Material	**Thermal conduc-tivity [W/m*K]**	**Density [kg/m³]**	**Specific heat [kJ/kg*K]**	**Dynamic viscosity [kg*m/s]**	**Emissivity**
Air	0,0263	1,1614	1007	$1{,}846{*}10^{-5}$	
FR-4	2,0	1900	930	10^{10}	0,9
Paddle	260,0	8780	385	10^{10}	
Encapsulant	0,8	1206	1000	10^{10}	0,9
Lead/Frame mixture	138,5	5750	631	10^{10}	
Chip	148,0	2330	712	10^{10}	
Foam Insulation	0,03	70	1000	10^{10}	0,9
Compact block	20,0	..	..		0,9
Compact leads	8,5	..	..		

5.3 MEASUREMENT AND MODELLING OF THE COMPONENT

The relative importance of the various internal heat paths depend considerably on the mounting method, the amount of metal in and number of wiring layers on the printed board, the package material, and the (possible) unusual surface treatment. The surface treatment has a strong effect on the surface temperature distribution, especially for components with relativly large surface areas.

For example, the surface temperature of a semiconductor component, measured with a thermocouple from only one location, cannot be used directly to determine the temperature of the active part of the component, because the surface temperature is not uniform. Because the package structures of semiconductor components typically conduct heat rather poorly, it is possible to use the three conductor (constantan-Cu-Fe) measurement method. In this method (Fig. 9) a piece of copper tape, for example with constantan and iron wires attached at the edges, is fastened to the component surface. The excellent heat conduction of the copper tape equalises the temperature difference between the two measurement points, and gives a good enough impression of the average surface temperature.

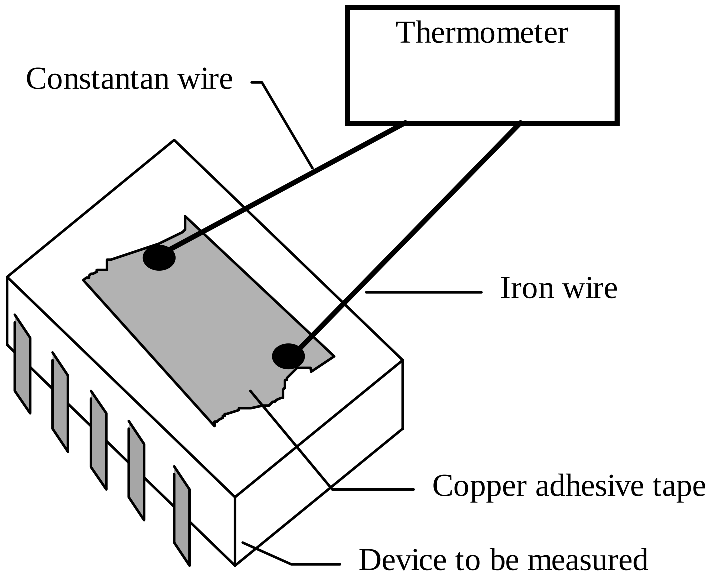


Figure 9. Use of copper tape to average the surface temperature of the measured device.

Alone this information is of little significance when one wants to know the temperature of the active part in the case under study. One must also be able to determine what fraction of the component power dissipation is transferred through this surface. This requires the measurement data to be fitted with the mathematical model that describes the internal thermal behaviour of the component.

The use of thermochromic liquid crystal paint is a surface temperature measurement method that is more comprehensive and easier to correlate with the modelling /5.5/. This method, which is easy to use and does not disturb the heat transfer paths, gives an accurate picture of the prevailing temperature distribution. The problem is how to illuminate and photograph an object which is often inaccessible. This can be solved by using viewing paths consisting of specially built transparent walls or an endoscope camera.

REFERENCES TO CHAPTER 5

5.1. Claassen, A.& Shaukatullah, H. Comparison of diodes and resistors for measuring chip temperature during thermal characterization of electronic packages using thermal test chips.

Thirteenth Annual IEEE Semiconductor Thermal Measurement and Management Symposium, Austin, TX, USA, 1997. Pp. 198 - 209.

5.2. Adams, V.H., Blackburn, D.L., Joshi, Y. & Berning, D.W. Issues in validating package compact thermal models for natural convection cooled electronic systems.

Thirteenth Annual IEEE Semiconductor Thermal Measurement and Management Symposium, Austin, TX, USA, 1997. Pp. 10 - 23.

5.3. Rosten, H.I. et al. Final report to SEMITHERM XIII on the European-funded project DELPHI - the Development of libraries and physical models for an integrated design environment.

Thirteenth Annual IEEE Semiconductor Thermal Measurement and Management Symposium, Austin, TX, USA, 1997. Pp. 73 - 91.

5.4. Vinke, H.& Lasance, C.J.M. Recent achievements in the thermal characterization of electronic devices by means of boundary condition independent compact models.

Thirteenth Annual IEEE Semiconductor-Thermal Measurement and Management Symposium, Austin, TX, USA, 1997. Pp. 32 - 39.

5.5. Azar, Kaveh & Farina, Dino J. Measuring chip temperatures with thermochromic liquid crystals. Electronics Cooling, vol. 3, no.1, January 1997. Pp. 16 - 20.

6 EXPERIMENTAL VERIFICATION

6.1 THE USE OF MEASUREMENTS AND TESTING IN VERIFICATION

Experimental verification is defined here as the testing and measurement of equipment prototypes at various stages of development, with the purpose of determining how well the unit in question complies with the stated thermal design objectives. Testing is defined as including both functional operation tests and conditioning to different internal operational loads and external environmental loads. To be confident of the quality of the experimental verification, it is necessary to use calibrated measurement and testing equipment which is a *sine qua non* condition in all quality assurance systems.

> Example: SFS-EN ISO 9000-1 (1994) Quality management and quality assurance standards. Part 1: Guidelines for selection and use.

Experimental verification is still imperative at the current (1997) level of technology, because thermal parameters are not known well enough (owing to the complexity of materials, components and constructions used) to verify the system by analytical means only. Modelling and simulations give fairly useful information about thermal characteristics when looking for viable options, but verification of the performance of the physical device cannot be entrusted to such methods.

In order to perform experimental verification it is advisable to combine the testing and related measurements in *test and measurement programs*, which also include the processing and analysis of results. The verification activity also assesses how well the respective tests serve the needs of product development and quality control.

Tests and measurements are designed in accordance with the development stage of the product:

1. Thermal testing of preliminary *structural models* when searching for correct thermal structural solutions.

2. Investigation of functional *prototypes* to determine the final characteristics before production.

3. Acquisition of *field data* from production units intended for users by monitoring devices (remote measurement technologies, service data from the warranty period).

These fundamental objectives must be taken into consideration when planning verification tests and measurements. Acquisition of field data is necessary to implement the learning mechanism in the company thermal design as well.

The tests and measurements must be designed in close co-operation with the mechanical, EMC and electrical design as well as other disciplines. Tests must be attached to each device prototype and selected appropriately to each prototype´s characteristics. The precursors of the product (such as cardboard, structure, and thermal models) characteristic of product development should be tested as appropriate to guide the thermal design and minimise the invariably complicated and time-consuming prototype manufacture.

Experimental verification using measurements and tests focuses on two technically essential areas:

- Verification of *thermal characteristics* (temperatures, powers, flows) with tests that simulate the operational conditions of a device.
- Verification of the *performance and reliability* of a device and detection of potential failure mechanisms related to temperature and its variations under the operational conditions of the device.

Operational conditions are here defined as the environmental conditions according to the specifications of the device, to which the device is exposed to during its life cycle in its operational location.

> The operational conditions are those in which the equipment exists during its useful life, e.g. between the minimum and maximum temperatures. Operation is simulated over this range using tests often performed only in extreme conditions, one condition at a time. The effects of changes of individual conditions are determined by varying one condition at a time, e.g. first temperature and thereafter operational power level.

The tests simulate these environments in order to acquire the necessary information on the behaviour of the product as quickly as possible with sufficient confidence. Some examples of thermally induced failure mechanisms leading to failure of the device are changes of component parameters beyond limits, catastrophic failures, and actuator failures caused by thermal expansion of structures.

Device measurements during testing should be designed where feasible to yield as much information as possible about the behaviour of the device with the fewest possible tests and measurements. Nonetheless, care must be taken to obtain the following information on functional and thermal characteristics during testing. Understanding of the thermal design must also be used to benefit both these areas.

- *Is the device functional or not*, and is it damaged or not? (go / no go check). Such checks can be performed at each stage of testing, and in extreme environments as well. However, such checks should not be limited to this type of yes/no information, as the random characteristics of components and structures can give either too good or too poor a result. Such measurements may in fact be a waste of test time, especially since adding a few parameter measurements produces more reliable and precise knowledge of important characteristics of the device, with relatively little trouble.
- *What measured performance values* does the device have under certain conditions and transient situations? What are the temperatures, power transfers, and e.g. air flows in certain test conditions? How close is one to the desirable values? Where are the biggest risks for failure? The measurement of different physical parameters makes possible an experimental sensitivity analysis for the product, relative to the conditions used in the test.

When assessing the thermal characteristics and reliability of the device different *thermal tests* (or climatic tests) are used which are either static or dynamic, with the purpose of simulating operation of the device. During thermal design the tests must be defined that will verify the different characteristics, and the associated conditions must be included in the modelling. The simplest way is to test the device under constant laboratory conditions, where the device is powered and its behaviour is measured. In this manner a preliminary and often sufficient impression of the success of the design is obtained. A more complete impression of the performance of the device may, however, be obtained with the aforementioned thermal tests, where the device operates in different extreme conditions in turn such as cold, hot, and normal laboratory conditions. These tests reveal the dynamic behaviour corresponding e.g. to the normal outdoor diurnal variation of thermal loads.

A separate subject is testing of the product under *exceptional conditions*, where temperature variation is combined e.g. with fierce rain and wind or simulations of sunshine corresponding to outdoor conditions. Such situations cause sudden rapide and large variations of temperature and heat transfer to the exterior surfaces of the device, which should be accounted for in thermal design. Other exceptional situations that should be accounted for include e.g. jamming of air ventilation holes by organisms, plants or litter.

In the verification of thermal design, the test conditions to be implemented and the test specifications should be planned jointly with those responsible for the environmental requirements of the device. This will save time and render the test results compatible with verification of environmental tolerance of the device.

There is extensive published literature on the *design of thermal and environmental testing* of devices. Some sources are listed below.

IEC 68-2, Environmental testing, Part 2 (IEC International Electrotechnical Commission). These standards (dozens of them) contain information on internationally agreed environmental test methods, where the stress levels used are chosen to be compatible with various environmental classifications.

The following tests are related to thermal design: IEC 68-2-1, Test Ab Cold, IEC 68-2-2, Test Bb Dry heat, IEC 68-2-14, Test Nb Change of temperature and IEC 68-2-30, Test Db Damp heat cyclic.

IEC 721-series environmental classification standards cover all environmental conditions present on Earth. The classification includes both the transportation and operation of the device in different protected or unprotected spaces (shelters) or vehicles. Examples of these classification standards are:

> **IEC 721-1**: 1990, Classification of environmental conditions -
> Part 1: Environmental parameters and their severities
> Amendment 1 (1992)
>
> **IEC 721-2-1**: 1982, Classification of environmental conditions -
> Part 2: Environmental conditions appearing in nature - Section 1: temperature and humidity
> Amendment 1 (1987)
>
> **IEC 721-3-0**: 1984, Classification of environmental conditions -
> Part 3: Classification of environmental parameters and their severities - Section 0: Introduction
> Amendment 1 (1987)
>
> **IEC 721-3-2**: 1985, Classification of environmental conditions -
> Part 3: Classification of **groups of environmental parameters and their severities; Transportation**

IEC 721-3-4: 1995, Classification of environmental conditions - Part 3: Classification of **groups of environmental parameters and their severities -** Section 4: **Stationary use at non-weatherprotected locations.**

SFS-käsikirja 108, *Ympäristöluokitus ja -testaus. 1989. Suomen standardisoimisliitto SFS ry. 76 p.* This handbook contains information on the principles of environmental classification and environmental testing. It also serves as a good guide for environmental classification standards and their application.

SFS-käsikirja 92, Abstracts of environmental tests. 1991. Suomen Standardisoimisliitto SFS ry. 150 p.

The Co-operation for Research and Development of Electronics in Finland, KOTEL (c/o VTT Automation, ProTechno) has published amongst others the following reports on testing of electronics devices.

KOTEL 203 *Ympäristötestauskäsikirja*. Espoo 1989. 166 p. This handbook (in Finnish) contains practical background knowledge of the prevailing environmental conditions on Earth, environmental classification, environmental test methods and guidance to planning of tests.

KOTEL 215 *Ympäristötestauskäsikirja*. Part II. Espoo 1994. 144 p. This second part contains formulae, tables and material data needed for test design of electronics devices.

6.2 MEASUREMENTS AND VERIFICATION

The thermal and air flow behaviour of an electronic device is investigated in experimental verification. This produces the measurement results called for by the test plan, as well as images of air flow obtained with smoke or tests based on other visual methods and observer notes of the flow behaviour of the device. Parameters to be measured are surface temperatures, air temperature, air humidity, air volumetric flow, velocity distributions, pressures and pressure differences. In the case of materials, components, and structural parts one can also measure fundamental quantities such as conductance, convection, and emission properties. In principle these data should be available in device development, but this often includes design and implementation of new components (modules), which requires one to delve further into these fundamental measurements.

The stages of experimental research include planning of measurements, execution of measurements, processing of measurement results, analysis of results, and reporting and documenting the data set. There is considerable literature published on the execution of experimental measurements, different measurement methods (such as /6.1/, /6.2/, /6.12...17/) and standards of separate measurement methods.

When experimental research is planned the measurement objects and measured quantities in the device are defined and the measuring apparatus is chosen. Selection of the apparatus is governed by economic resources and the physical and measurement technical properties, and usefulness of the apparatus. Properties to be considered are performance, accuracy of the method, measurement frequency, ability to observe measured values in order to monitor and control the test, and the storage of measurement results. In the selection of measurement sensors appropriate to the measurement conditions, the sensor accuracy, size, and reaction speed must be considered. Other considerations affecting selection of the measurement system include the training of operations personnel, maintainability of the equipment, and ease of calibration.

When assessing the reliability of measurements and mapping the errors, one must consider among others things the measurement error, systematic error, random error, and inaccuracy and drift of the measuring device /6.17/. When presenting the measurement results, errors different sources are estimated with error limits. The presentation format of the measurement results is **y** ± **dy**, where **y** is the value of the measured quantity and **dy** is the error in the measurement results caused by various factors.

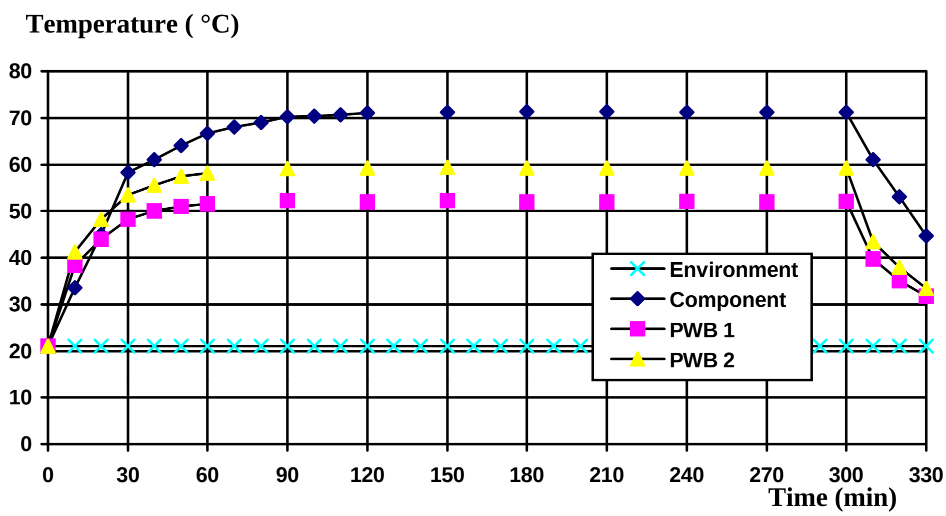


Figure 10. Warm-up of the device during measurements.

Figure 10 is an example of normal warming up of a device. When planning the measurement the time constants of different parts of the device must be considered in order to perform the measurements at the correct times. Figure 10 shows the temperatures measured from a television set The voltages are switched on at time zero. The warm-up of a fairly hot, large component continues when measured from its surface even past 120 min after voltage switch-on, although the circuit board temperature near the component stabilised already at 90 min. The same rate of change is seen after voltage switch-off at 300 min. In this case one must wait at least 120 min before an accurate impression of the static performance of the device is obtained. Correspondingly in thermal cycling tests sufficient stabilisation times must be reserved to ensure that all parts have reached their final temperature.

In verification at least the following items are covered:
- Existence of a measurement program - Existence of a test program - Processing and documentation of results (assessment of usefulness of results, comparison with calculated results) - Do the measurements and tests cover all structural models and field conditions? - Definition of the contents of measurements (temperatures, surfaces, air, flow, heat power, etc.). What is worth measuring and in what phase? - Definition of physical measurement locations. Do they also correspond to the thermal design and the model? - Definition of measurement timing. Have sufficient times for thermal equilibrium been ascertained, have the different time constants of different parts and thermal capacities been considered when studying transients (for example the reaction of the last components at the end of a long path)? - Definition of the measurement (test) conditions. Have external disturbances been considered, and are the measurements performed in operating conditions or representative test conditions? - The measurement methods and their applicability to the measurements, inaccuracy, measurement equipment, and relation to the stated design margins - Decision procedure in interpretation of observations - Field measurements under operating conditions - Measurements of materials, boundary surfaces and components, possible needs - Utilisation of feedback information, pruning of measurements based on design experience and/or change of measurement content when making new versions of the product.

Based on the preceding discussion, measurements related to design verification should extend from the early structural models (even cardboard models) to the final product and even to the field where feedback information of real operational environments can be obtained. The structural/thermal models, which are simplified models of the functional device, are verified to the accuracy level appropriate for the current phase. These measurements performed in different phases must be included as part of the thermal design to gain the fullest possible information on the accuracy of the design criteria.

Documentation of the measurement plans and results is a mandatory part of the utilisation of the results. For example, the existence of result sheets prepared in advance certifies that the desired properties have been measured and reduces the need for supplementary measurements or reprocessing of the results.

6.3 SURFACE TEMPERATURE

6.3.1 Selection of verification objects

Surface temperature is here defined as the measured temperature at the surface of some mechanical part. In the sense of measurement technology, surface temperature is a parameter determined by the measurement method used, describing either one point on the measured surface or some kind of average value of the temperature over the surface.

All measurement methods have typical error sources which must be considered. The basic starting point of Figure 11 is that the measurement method does not disturb local thermal conditions. In this case, for example, the sensor must not change the thermal properties of the surface. If the sensor is large it may cause conduction failures, or behave like a heat sink, and covering it with aluminum tape may affect the radiation properties of the surface. On the other hand the surface temperatures of the measured device can vary because of structural details. Therefore it is important in the plans and measurements to foresee these items.

Crude models of components and parts are often used in thermal design, where the powers are known but the internal structure is assumed to be a simple block, resulting in the temperature of the part being an average of that of the component. Information on real surface temperatures is thus lost and no comparable measurement objects are available for verification.

The starting point for verification is to check how the surface temperatures and measurement locations have been defined in thermal design. Are they

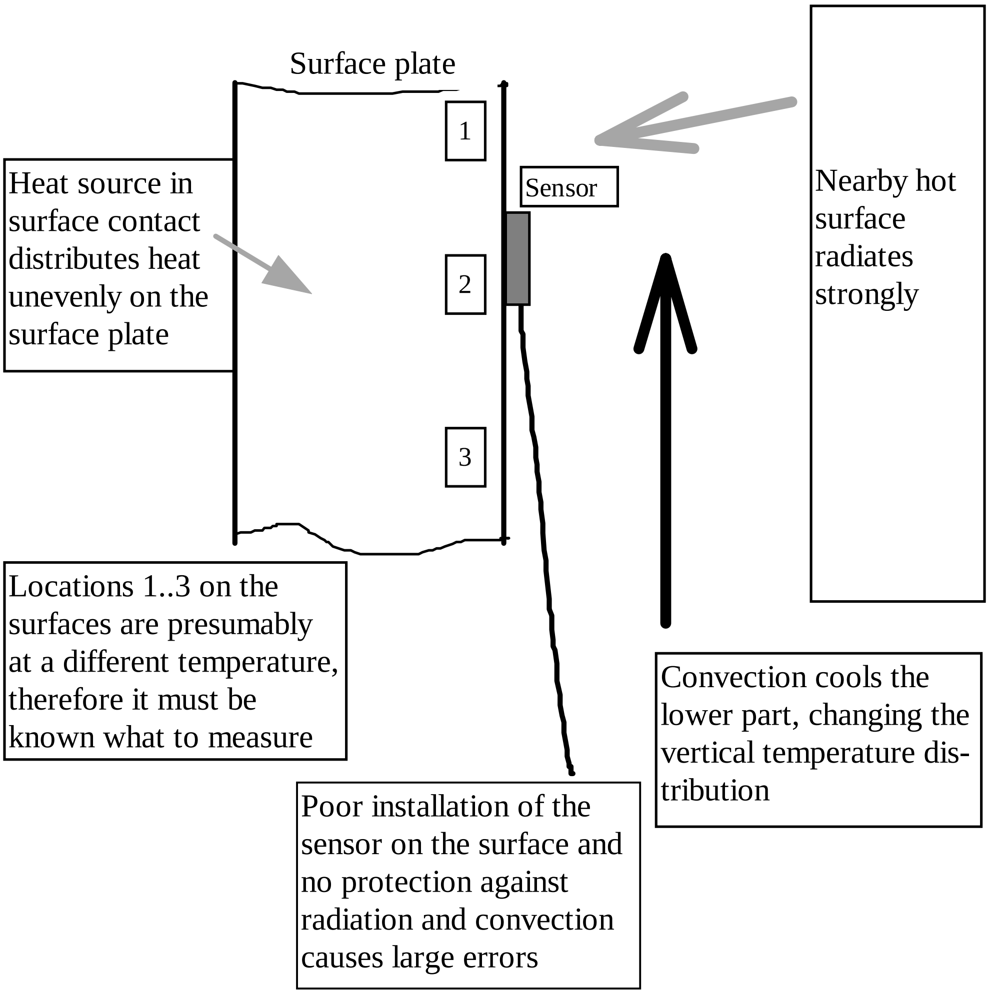


Figure 11. Measurement of surface temperature.

measurable with existing methods with sufficient accuracy, and have these reference points been used in measurements so that comparison of the measurement results with the plan is possible? If there are no defined measurement locations in the thermal design, it should be checked whether objects selected for measurements can be used to verify the desired information from the design.

Here verification is divided into assessment of measurements of the **device's exterior surfaces and interior,** and of measurements of the **component surface temperatures**. The available assortment of measurement methods depends on these objects. Concurrently, the effect of the prevailing environment (ventilation, various sources of heat, sunshine) on the results in the measurement situation must be checked to confirm that the measurement situation corresponds well enough to the expected operating conditions and that the local environment in question is known sufficiently.

If the measurements are performed e.g. at normal room temperature, one must check how much the expected operational conditions deviate from it and correct the results to correspond to extreme operational conditions. In laboratory conditions, in climate tests, and in the field, it can be difficult to measure the outer surface temperature of the same objects under all conditions. In the field external disturbances such as rain, freezing, sun, wind and mechanical damage interfere with the measurements. Therefore when selecting measurement objects (this is done by the designer and tester) one should consider, when using sensors, the possibility to measure surface temperatures also from the inner surfaces, so that the same measurement objects are obtained that are sensible to use in both test and field conditions. This also serves possible data acquisition in the field and its usefulness.

6.3.2 Choice of measurement timing

In verification, all objects whose surface temperature is to be measured are examined to ensure that the selected measurement times and durations are consistent, that the thermal time constants of different parts do not cause errors in the measurement results, and that the time constants of the sensors are appropriate for the rate of change of the measured phenomena.

In measurement at *thermal equilibrium* it must be ascertained that the device has reached its final temperature. For example, the warm-up of a device the size of a microcomputer or television receiver lasts at least an hour. In practice, especially when using natural convection the time to thermal equilibirum for such devices can be 3 hours. Correspondingly, there can be critical components in the device, which are at the end of a long thermal path and therefore respond to temperature changes with a considerable time lag.

When studying the effects of *external temperature changes* the different thermal time constants of the measurement objects (or the whole device) must be determined so that a sufficient settling time is reserved, especially when testing at extreme temperatures.

Some typical temperature measurements of different parts of a cabinet in a thermal cycling test are presented in Figure 12. The measurements were performed in a changing temperature of the environment. According to the figure not even the surface temperature of the device had time to reach equilibrium at the extreme temperatures of the test, not to mention the interior and processor surface temperatures. If the purpose of the test was to measure the behaviour at extreme temperatures and not merely the behaviour during transients, the stabilisation times chosen were too short.

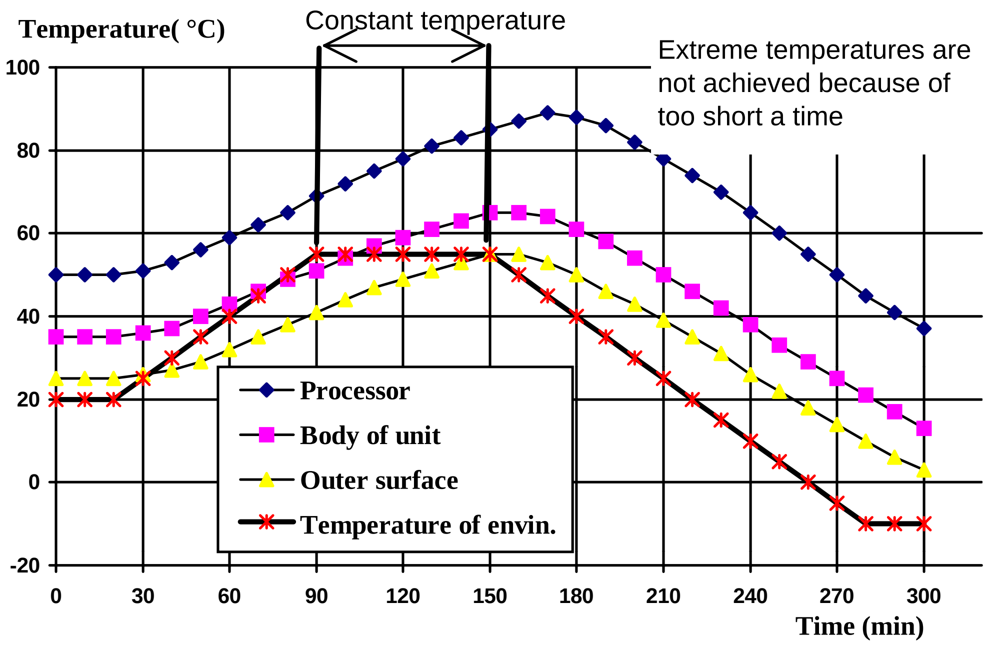


Figure 12. Poorly designed test for an electronic equipment.

Figure 12 demonstrates the importance of measuring actual interior temperatures of the equipment during the tests rather than merely inspecting the functional properties (go / no go).

6.3.3 Exterior surface temperature of the device

With measurements of the exterior surface temperatures of the device the thermal ergonomy, performance of cooling and partially the magnitude of the heat power can be checked as appropriate. In addition, when checking the heat transfer characteristics of the exterior surfaces, the surface temperatures should be measured. Verification is made of the objectives set for the specification and measurement of exterior surface temperatures. Similarly a check is made of the purpose for which the temperatures of the measurement points will be used.

Ergonomy and utilisation of waste heat

One design goal is to keep the exterior surfaces of the device cool enough-in all circumstances that the user is not hurt when touching them, or the surface of the device does not reek when there is dust on it. A design goal for a device designed for outdoor, humid conditions might be to keep the exterior surfaces e.g. 3...5°C warmer than the environment in order to dry the surface and reduce corrosion.

In such a situation it is advisable to use an infrared measurement instrument or an infrared camera, which gives a general impression of the whole exterior surface. In this case there must be fairly good knowledge of the emissivities of the surfaces or experience of infrared measurement technology and its applicability. On the other hand, the tester's own senses or easy-to-use surface temperature measurement devices may be enough for the measurement, provided the external conditions correspond to the worst operational situation. One should ensure that the highest allowable surface temperatures which affect ergonomy have been specified.

A measurement inaccuracy of ±5°C is often sufficient. Correctly used an infrared camera may have inaccuracy of ±2°C and a resolution of ±0,5°C. However, the temperature rise to be ascertained is only a few degrees, an inaccuracy of e.g. ±0,5°C should be sought, which is usually achievable only with calibrated surface sensors.

Performance of cooling

The temperatures of exterior surfaces depict to some extent the cooling performance of the device both by absolute values and by spatial variation. However, the exterior surface temperatures do not give an adequate picture of the behaviour of internal parts of the device, therefore the device's performance cannot be established solely from these temperatures. Exterior surface temperatures can be used for monitoring time-dependent warming of the device and the effects of external temperature changes. However, well-insulated exterior surfaces do tend to follow the environment temperature. The thermal design must include an assessment of the suitability of the exterior surfaces for understanding the cooling performance and what measurement points should be used.

Temperature sensors which supply point-wise values as a function of time are most appropriate for exact measurement of these properties. A sufficient measurement inaccuracy in these cases is ±2°C.

Magnitude of thermal power

When a reliable picture of the heat power of the device is desired, including the effects of convection, emission and conductance, one must also know the electrical waste power and surface temperatures of different sides of the device and their changes. However, when strong ventilation or separate coolers are used, and when the surfaces are thermally well insulated, the exterior surface temperatures of the device have a weak correlation with its heat power.

In thermal power measurements of devices it is essential to ascertain that the air flows and temperature of the environment and of surfaces directed towards the measured device are known sufficiently.

Surface temperature sensors, such as thermocouples, which monitor the temperatures of desired locations as a function of time during testing, are most suitable for this measurement. A sufficient measurement accuracy in these cases is often ±2°C, although in some cases probably ±1°C is needed when the total warming is fairly low.

Effect of exterior surface form and material on thermal characteristics

When inspecting exterior surface measurement objects the form of the device, which might be a cabinet, case or plug-in unit, must be considered. The form of the exterior surface is always variable depending on the environment for which it is intended. The exterior surfaces also contain holes, for example for ventilation. The effect of surface forms, holes and surface material on temperature and its evenness must be assessed when selecting measurement points and using the measurement results.

The measurement locations should be representative of the surface. In other words if the temperatures of the selected points represent, for example, 90 % of the surface, the measurement can be considered as fully adequate. In simpler cases temperature measurements from a few points or even one point are satisfactory. For more complex surfaces, which are significant for ergonomy or heat transfer, more measurement points or a heat camera must be used to map the whole surface. When using infrared measurements the emissivities of the surfaces must be known with reasonable inaccuracy (±0,1).

The local environment also contributes to the results of surface temperature measurements. For example, very hot or cold neighbouring surfaces can produce errors, as can a strong external air flow, or sunshine (through the window or outdoors).

6.3.4 Surface temperatures of interior parts of the device

Knowledge of surface temperatures of interior parts of the device is needed primarily to ascertain that the performed thermal design has led to a desired temperature distribution inside the device and that the heat transfer mechanisms function as planned. In verification the surface temperatures can be used to ascertain whether all useful heat transfer means have been used rationally in the device. This becomes especially apparent when large temperature differences arise between neighbouring parts.

The fundamental objective is usually to ascertain that the hottest parts of the structure are within the specified limits. However, measurement of also the coldest parts can be useful, for example to verify the performance of the thermal design and identify the corrosion risk of outdoor equipment. Measurement data are needed from units, frame structures, connector thermal conductances, circuit boards and component surfaces.

In the verification of internal measurements, one should first check the interior surface measurement objects included in the plan and their usage, and assess their relevance and the possibilities of error with respect to the thermal design. In particular, assessment should be made of the capability of the selected measurements to detect excessive temperature differences between structural parts, which may result e.g. from poorly contacted interface surfaces.

For example, a typical design fault is to leave circuit boards floating (in the thermal sense), thereby failing to utilise the mechanism of conductance to distribute heat to the environment.

Another example of erroneous surface temperature design objective or faulty design is that the interior parts are cooled as efficiently as possible without considering the behaviour of the coldest objects. When air is ingested into the device from the outside it is usually humid. As this is blown towards the interiors of the device, the temperatures remain low at the entrance but the humidity stays high (> 50 %), causing corrosion. If this air needs to be cooled further during the hot season, its humidity can rise to over 90 % which significantly accelerates corrosion. This is easily avoided by using the heat power of the device itself to raise the temperature at the entrance and avoid excess cooling at locations where air is supplied to the device. In such situations the entering air should be dried before blowing into the device.

Useful measurement technology

From the general viewpoint of measurement technology, no matter how good the technology it is fairly complicated to measure interior surface temperatures owing to the numerous measurement points. When a quick impression of interior surface temperatures of the device is desired, the device can be temporarily equipped with plastic walls transparent to thermal radiation, conserving the air flow properties but still allowing the parts so exposed to be imaged with an infrared camera (For example, 6 μm mylar DuPont Co.; the infrared permeability spectrum of the material must be inspected in each case /6.5/). Another possibility is to open an operational device briefly and remove circuit boards or units for imaging. To improve the usefulness of these results it would be appropriate to mark on the surface of the imaged object a few reference points also included in the thermal design, and to measure the temperatures from these reference points with e.g. thermocouples simultaneously with the camera imaging.

Surface temperatures obtained using an infrared camera have, in the best case, an inaccuracy of no better than ±2°C If the device does not contain shiny surfaces, the emissivities are all of similar magnitude and possible imaging failures are corrected. With this kind of measurement surfaces significantly hotter than their environment always produce errors in their vicinity.

A more reliable picture of temperatures of individual points is obtained, for example, with thermocouples, which can achieve absolute inaccuracies better than ±1°C. When using these, special attention must be paid to installation of the sensors on the surface and insulation from the effects of the environment, since the surfaces are usually very close to each other. In the same way care should be taken to avoid influencies on the temperature of the measured object due to the good thermal conductivity of sensor wires. Steep temperature differences can exist in the structures, which should be mapped before the final choice of sensor installation location(s) so that position inaccuracies do not cause major errors. Corresponding errors in the surface temperatures can be caused by strong convection from a fan or radiation from a hot surface if the temperature sensor is not well protected from external disturbances, for example with aluminium tape. The sensors should be reasonable small to avoid disturbing the object under measurement and more easily protect it from external disturbancies.

Heat distribution and transfer paths in structures

Because it is usually desired to distribute the heat fairly evenly across the device, so that the hottest parts are as cool as possible, one of the main goals of verification is to ascertain that the temperature distribution is relatively even over the component boards, as well as in the frame structures. In this regard it is advisable to look for large temperature differences between neighbouring structural parts, which would indicate open circuits in the heat transfer paths.

As part of the verification process the hottest and coldest areas are inspected and the conformity of different objects to the designed temperature distribution is ascertained.

In order to inspect the heat distribution, surface temperature measurements must be extended from component boards through connectors and frame structures to possible mother boards and interior surfaces of the device, in order to verify the use of all feasible heat transfer paths. A good rule of thumb is that all structures containing metal, such as metal frames, connectors and cable bundles, can serve as effective heat transfer paths away from the component boards and units. For example using the motherboard surface as a heat removal path is possible if multi-pin board connectors (whose metal conductors transfer heat well) are used on the circuit board edges. Correspondingly, poorer heat transfer materials like most plastics are likely to reduce heat transfer possibilities.

6.3.5 Surface temperature of the component board

The performance of the heat transfer paths of a component board containing printed wiring (layout) and mounted components is verified using the measured surface temperatures. The surface temperature of the actual circuit board itself is conceptually rather diffuse and its absolute value is less important than the temperatures of the components on the board. An important verification object is, however, the performance of the junctions between the components and the board and conductors as a heat transfer path.

Figure 13 shows how the junctions of the circuit board and the components are studied with the intention of demonstrating the significance of the correct choice and interpretation of measurement points. There is one heat producing transformer and several hot working components. One quarter (1 W) of the waste power (4 W) of the transformer is deposited in the printed circuit board. When, for example, the circuit board temperature as seen by the transformer is to be determined, it is important to recognise the significant heat transfer paths, which in this case are the conductors. The sensors must be located at these junctions. The plastics of the transformer do not in this case conduct much heat to the circuit board because, among other things, the frame structure has only a small contact surface area with the printed circuit board.

Useful measurement technology

Technologies applicable to surface temperature measurements of component boards are the same as for measurements of the device’s interior parts. However, owing to the small scale and neighbouring hot and cool components, it is especially important not to mistakenly measure a temperature to the side of the heat transfer path when seeking to verify the heat transfer paths of a component. Note that this point must be verified independently. Errors (e.g. 5...10°C) easily arise due to the large difference in thermal conductance between the circuit board metallic conductors and insulated areas. It may, for example, be difficult to find a large enough area

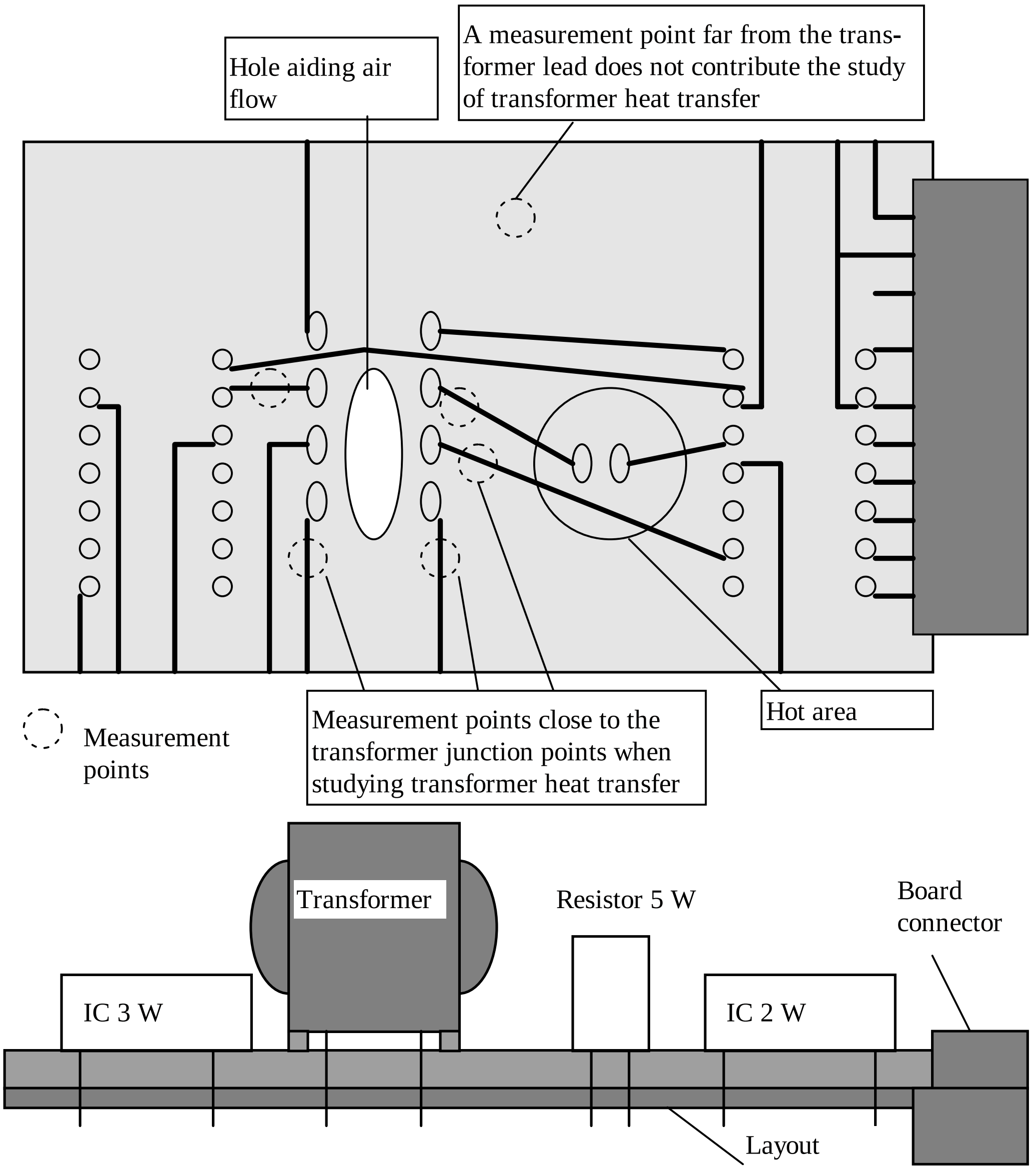


Figure 13. Temperature measurement objects on the component board.

on the printed wiring board to attach the sensor reliably. In this case it is tempting to attach the sensor where it is easiest. When using thermocouples which owing to their small size are suitable for these measurements, it must be ascertained that the installation technique of the sensors is sufficiently reliable and that attachment is certain. A loose contact or air gap between the sensor and the circuit board surface easily causes errors of the order of 5...10°C. In addition, the thickness of the tape may disturb temperature measurements if a thick layer is needed for electrical insulation. A good solution is, for example, to use Kapton tape on printed wiring board on which aluminium tape is used to attach and cover the sensor. In any event verification must be made of the adequacy of such arrangements.

6.3.6 Surface temperature of a component

The surface temperature of a component installed on a component board must be known in order to estimate the temperatures of the component´s critical internal parts. The surface temperature can be used in a limited way to estimate the heat transfer from the component to the circuit board and surrounding air.

Depending on how much knowledge of the component characteristics is available, it is often worthwhile to study in greater detail the surface temperatures of at least the most critical components. If no information is available concerning the component’s internal structure, surface temperature measurements can lead to large errors when estimating the internal temperature of the component. If in the thermal design only a body of a certain physical size with constant isotropic thermal conductance has been used to model the component, the temperature of the upper surface, for example, will not necessarily have good correlation with the component interior temperature, because the unaccounted-for heat transfer through the leads changes the temperature distribution. (See chapter 5 Components.)

Useful measurement technology

In principle, the same measurement techniques can be used for measuring the component surface temperatures as for the circuit board. However, the small area and irregular surface of the component complicate the use of sensors normally used for circuit board temperature measurement. For example, in an extreme situation the sensor mass can be too big in relation to the component. (See also chapter 5 Components.)

Figures 14 and 15 show a few representative cases of mounting temperature sensors on components. The sensor can be installed on the component primarily by gluing (araldite), but also fastening with tape is possible with integrated circuits. A frequently encountered problem is the small space and associated prospect of disturbing convection and emission from the component surface to the surrounding air. A sensor between an integrated circuit and a circuit board shows an average of the component bottom surface and circuit board surface temperatures, producing layout-dependant errors. (See also chapter 5.)

Minimally disturbed surface temperature measurements can be performed by painting the component surface with TLC pigments (TLC Thermo-chromic liquid crystals /6.3 and 6.4/), in which case the measurement is based on the surface colour.

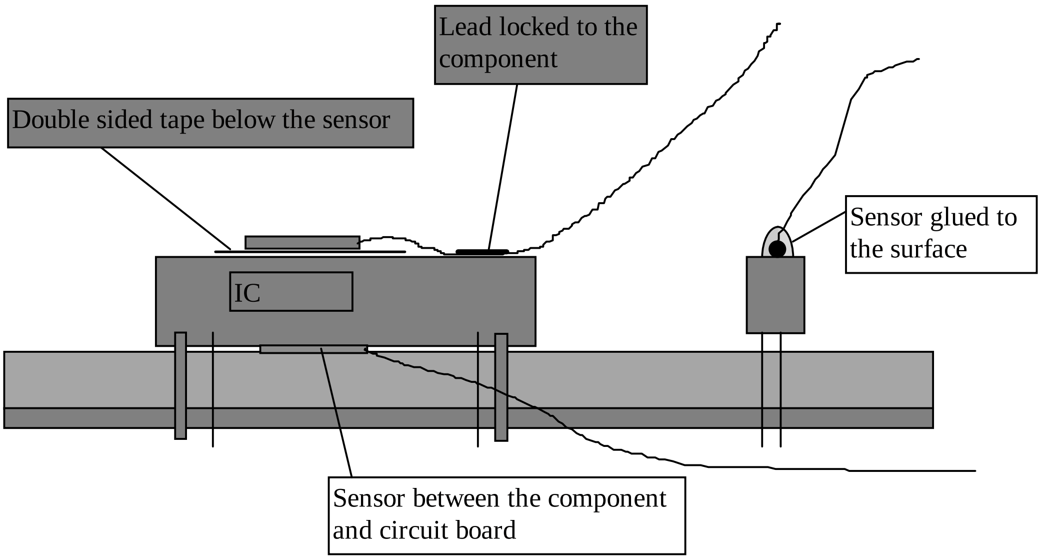


Figure 14. Installation of thermocouples on components.

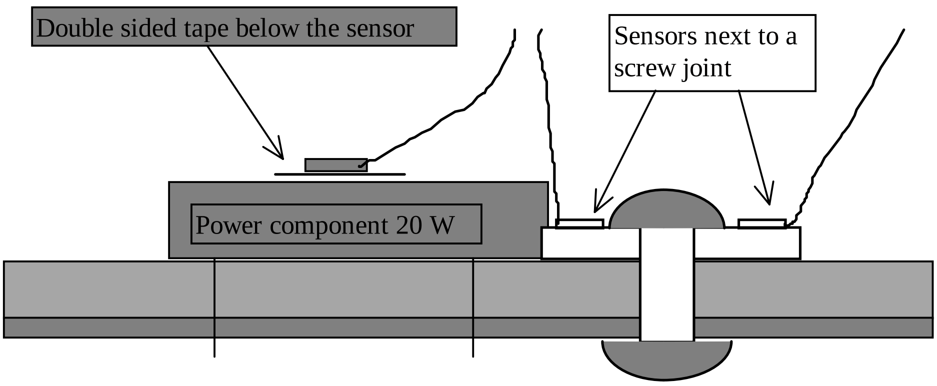


Figure 15. Installation of thermocouples on a power component.

6.4 AIR TEMPERATURE MEASUREMENT /6.6/

The knowledge of air temperature is needed in an electronic device to estimate the power losses (temperature difference between input and output air), to determine the environment´s temperature, and to assess the success of the thermal design of the device´s internal parts.

Air temperature /6.6/ inside the device is a *hard-to-define* quantity, because even in a steady state the temperature is different in each point because of energy release from heat-generating components. The temperature field depends on the heat generated by nearby components, geometry and air flow velocity. The flow field depends in a complicated way on the component power generation, and the form and extent of air ducts. Owing to these matters the measurement of air temperatures inside the electronics device is a complicated procedure. The problem is shown in Figure 11, where the air temperature varies in different locations and also as a function of time. The temperature of the device´s internal air is therefore in practise not often measured, instead one is content with the more easily controlled surface temperature measurement.

When an air temperature measurement is needed, the desired knowledge can be obtained with reasonable effort when a few basic principles are followed in order to avoid errors. Figure 16 shows a thermocouple located in a cavity the walls of which are isothermal at T_s and where the air flow temperature is T_a. If the wall temperature is significantly different from the air temperature the radiative heat transfer from the walls can cause considerable errors in the measurement result.

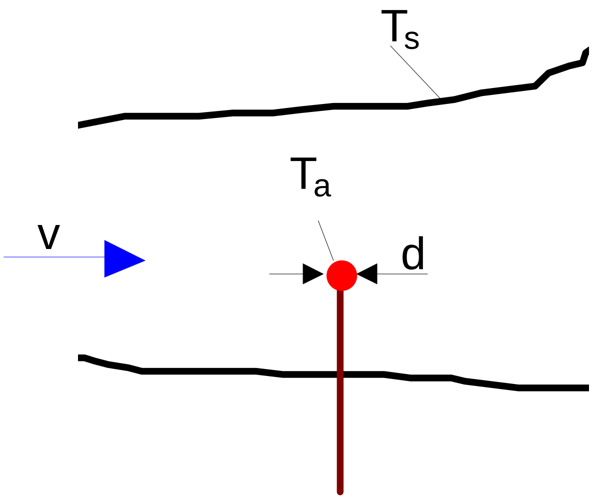


Figure 16. A thermocouple in an air temperature measurement /6.6/.

By using sufficiently small sensors this problem can be eliminated almost completely. In practice with a wall temperature range of 0...140°C and air temperature varying in the same range, an error of less than 0,5°C due to radiative heating can be attained when using a thermocouple with a diameter smaller than 50 µm. If the sensor diameter is 1 mm the corresponding error can be as much as 5°C.

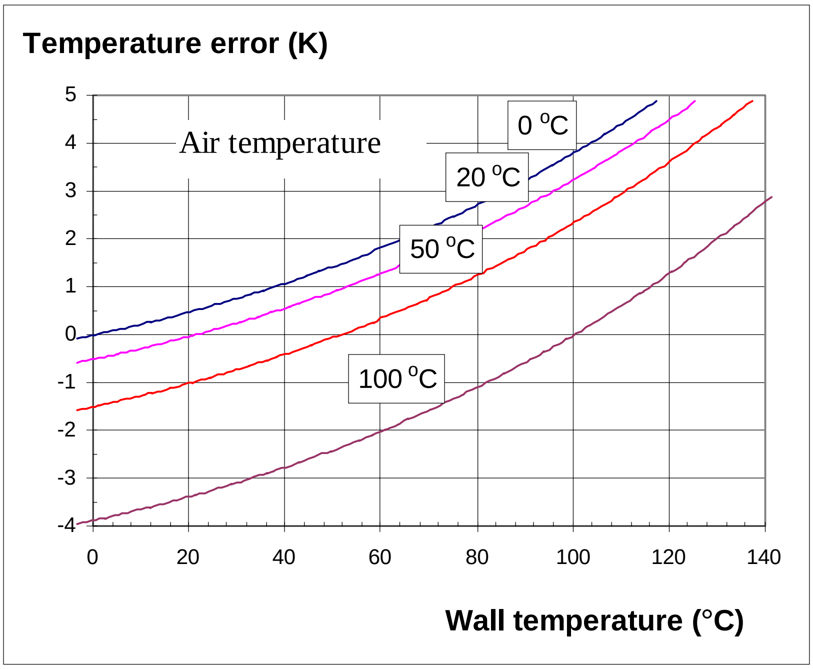


Figure 17. Error caused by a hot surface, thermocouple ∅ 1 mm.

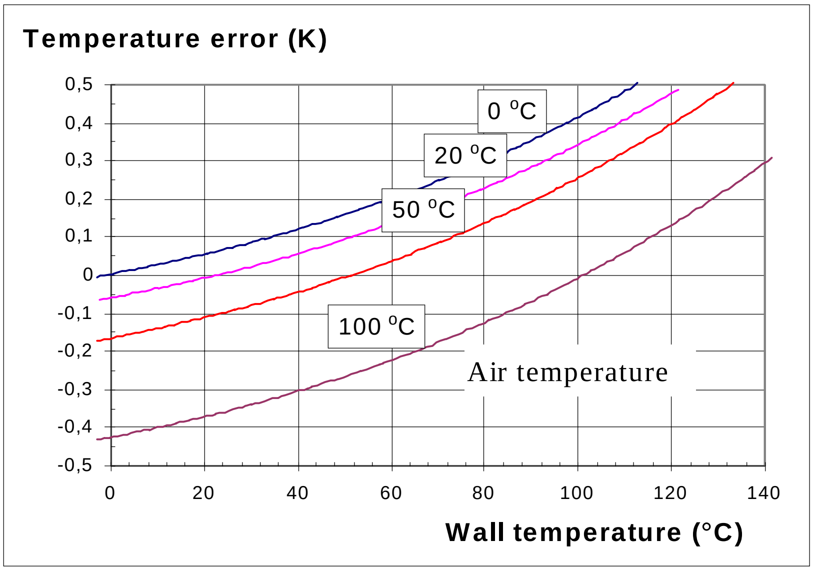


Figure 18. Error caused by a hot surface, thermocouple ∅ 50 µm.

In Figure 17 /6.6/ the error in a thermocouple reading caused by thermal radiation from a hot component (wall) is presented as a function of the surface temperature, for a sensor of 1 mm diameter positioned in the measurement field at a given air temperature, which is presented as a parameter.

Figure 18 shows similar results for a ∅ 50 µm sensor. When using such thin sensors, the air temperature can be measured relatively reliably even in confined spaces and close to surfaces with considerably different temperatures without fear of a large error caused by radiative heat transfer.

The air temperature in a device case can in principle be measured with several different sensor types, of which the two most important are various thermocouples and a forward conducting semiconductor diode. The latter is commercially available as an integrated circuit in a semiconductor or microchip case. The attainable absolute accuracy is typically 0,5 K and sensitivity 1 mA/K, /6.7 and 6.8/. These sensors are not the most appropriate for air temperature measurement in a device case, because the size of their cases is at least of the order of a few millimeteres. Therefore the time constant is rather long and the radiative correction is significant, as noted earlier.

Thermocouples exist in many varieties, but in principle all are appropriate for the tasks required here. Thermocouple properties are presented in Table 2. When relative temperatures are measured, the thermocouple accuracy is so good that the calibration curve supplied by the manufacturer can be used. If one desires to improve the absolute accuracy, one can either calibrate an ordinary thermocouple *in situ* or use thermocouples individually calibrated by the manufacturer.

Table 2. Properties of various thermocouples in IEC 584-1 /6.9/

Type	Material	Measurement range (^{o}C)	Sensitivity (µV/K) (20^{o}C)
E	NiCr-CuNi	-40...+900	60
S	PtRh10%-Pt	0...+1600	60
T	Cu-CuNi	-200...+350	40
J	Fe-CuNi	-200...+750	51

CuNi = Constantan (CuNiMn)

When measuring the *device cabinet heat power* one can use the previously described air temperature measurement techniques, for example in the case of free convection (Figure 19). In the device case of Figure 19 there is an entrance air hole in the bottom and an exit hole in the top. There is no fan, therefore air exchange is by free convection. Air flows through the cabinet along the pressure difference caused by the buoyant force. Maximum pressure levels are determined by the maximum hydrostatic pressure difference outside the cabinet, and the average temperature inside the cabinet. The buoyancy is dissipated mainly into the flow resistance in the holes. The flow resistance inside the case is usually much smaller than at the holes, because the air flow velocity inside is smaller than at the holes.

A characteristic value of the device´s internal air temperature is obtained by measuring the temperatures at the entry and exit holes and by determining the total flow.

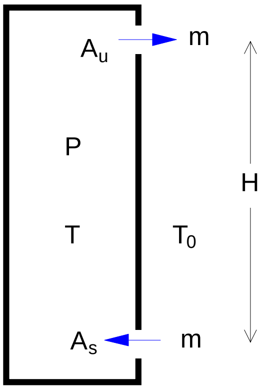


Figure 19. A device cabinet with natural ventilation.

* size 1,5 m x 0,6 m x 0,4 m
* power loss typical 170 W, maximum 500 W
* the cabinet contains frames each having about 15 component boards
* H = 1234 mm
* A_u = 409 x 133 mm^2 (nominal size)
* A_s = 409 x 112 mm^2 (nominal size)

The temperature rise $\Delta T = T - T_0$ of such a cabinet as a function of cabinet power /6.6/ and /6.10/ is shown in Figure 20. The nominal size of holes (Figure 19) is 100 %, from which the areas are changed by ±30 % to describe the effect of the size of ventilation holes.

From the graph in Figure 20 it is possible to estimate the power of the cabinet when the temperature difference is measured from the input and output holes. Accordingly, the air flow speed can be measured at various power levels or estimates of power at different air flows and hole sizes.

In Figure 21 the air flow velocity in the lower ventilation hole is shown as a function of power for different hole sizes. In the nominal power range the air flow velocities are 0,3…0,5 m/s. They are so small that their measurement is not easy.

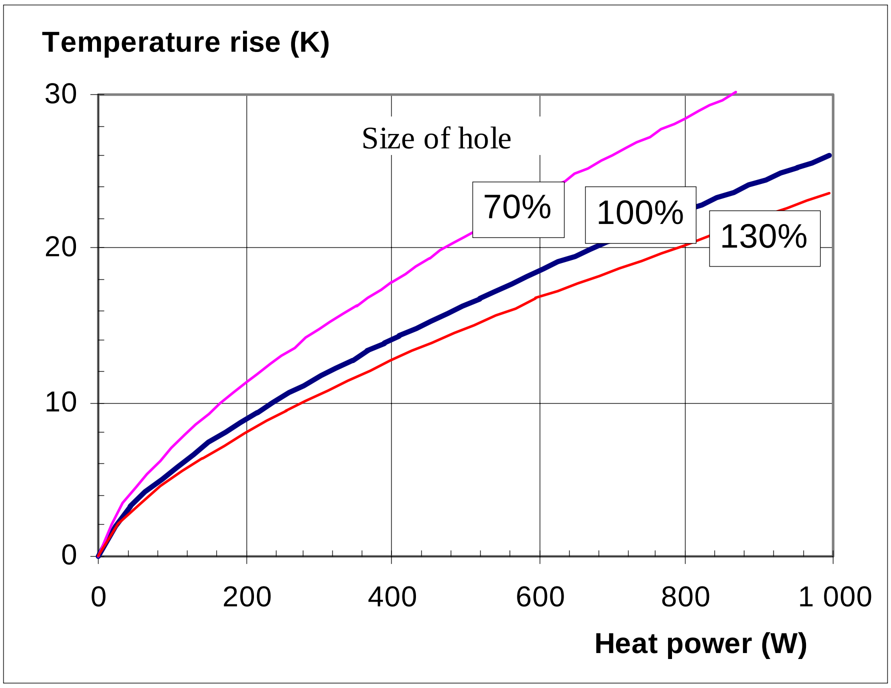


Figure 20. Temperature of the output air as a function of cabinet power with different hole sizes. 100% is nominal hole size, 70% and 130% are respectively smaller and larger.

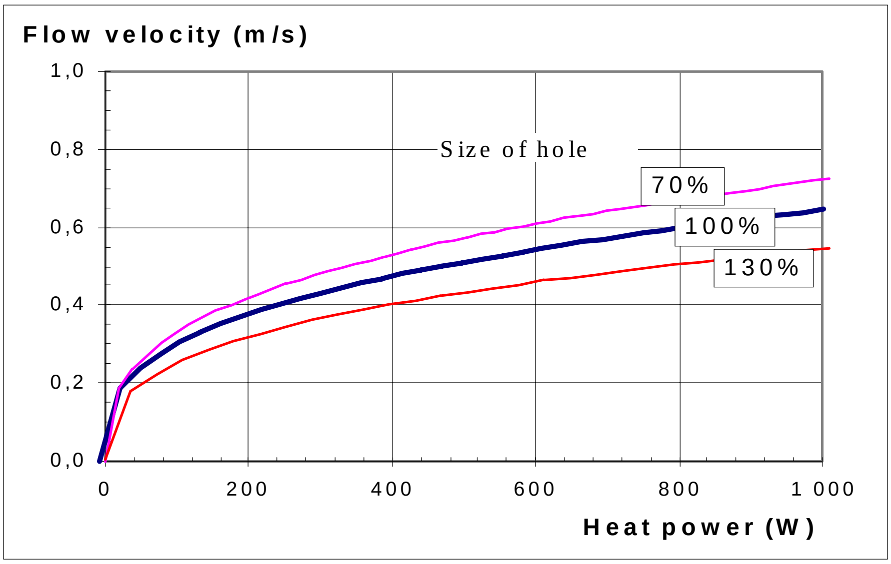


Figure 21. Air flow velocity in the lower ventilation hole with different sizes (70 %, 100 % and 130 % as above).

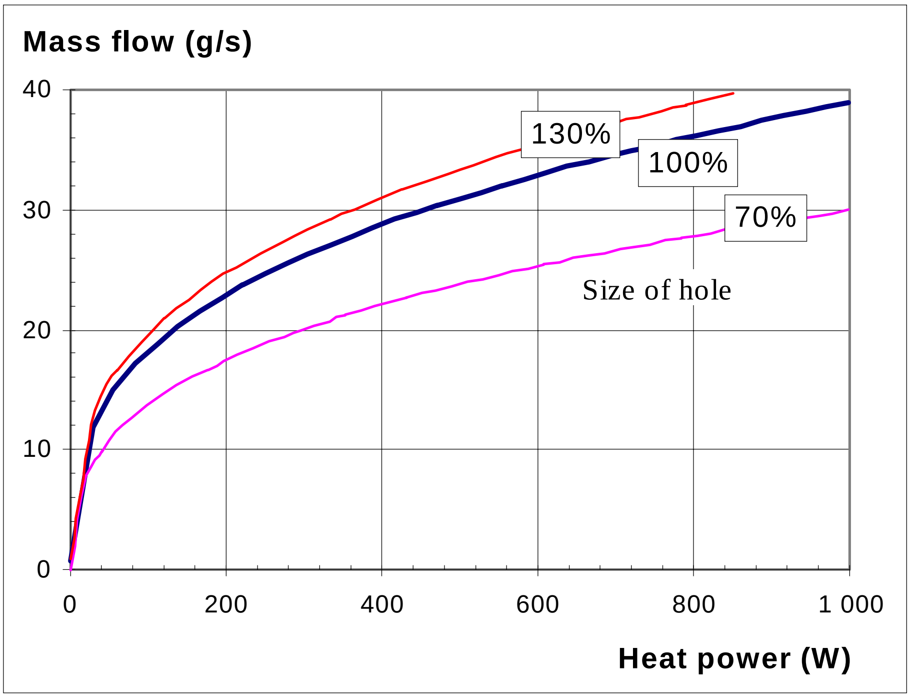


Figure 22. Mass flow through cabinet holes as a function of heat power with different hole sizes (70 %, 100 % and 130 % as above).

The relationship used to calculate these curves /6.6/ treats the cabinet as a fully stirred reactor whose internal temperature is throughout the same and in this case equal to that of the exhausting air. This is a rather decisive and not fully correct assumption especially close to the entrance hole, but for the whole cabinet on the average results correspond to practical experiences.

The heat power P in the case is given by

$P = c\dot{m}\Delta T$ where $\Delta T = T - T_0$ and air mass flow rate $\dot{m}$ (1)

When the height of the holes is assumed small in the relation to cabinet height H, the following equation can be written for the pressure difference:

$$\Delta p_s + \rho g H + \Delta p_u = \rho_0 g H \quad (2)$$

By applying Bernoulli´s equation along a streamline of cooling air between the entry and exit holes, equation (6) can be deduced for the relative temperature rise in dimensionless form.

The mass flow $\dot{m}$ in the input and output holes (Figure 22) depends on the pressure difference Δp_s or Δp_u acting across the holes as follows:

$$\dot{m} = \rho_0 C_s A_s \sqrt{\frac{2\Delta p_s}{\rho_0}} \quad (3)$$

$$\dot{m} = \rho C_u A_u \sqrt{\frac{2\Delta p_u}{\rho}} \quad (4)$$

where the C´s are the pressure coefficients of the holes and the A´s their areas. The air density in the ambient and cabinet are ρ_0 and ρ respectively. The air density can be related to the temperature T with the equation of state for an ideal gas, which when cast in density form is

$$\rho = \frac{pM}{RT} \quad (5)$$

The relative temperature rise is then

$$\frac{\Delta T}{T} = \left[1 + \left(\frac{C_u A_u}{C_s A_s}\right)^2\right]^{1/3} \left(\frac{P}{c C_s A_s \rho_0 T_0 \sqrt{2gH}}\right)^{2/3} \quad (6)$$

This formula gives slightly too high a value for the air temperature rise, because part of the heat power is conducted through the case walls, which is not accounted for in this simple adiabatic model. A similar effect is produced by neglecting the cabinet internal flow resistance. However, the flow resistance is small by comparison with the flow resistance of the cabinet holes.

Based on the temperature rise ΔT the mass flow in the holes can be calculated from the formula

$$\dot{m} = \frac{P}{c\Delta T} \quad (7)$$

The mean flow velocity in the lower hole is obtained with the formula

$$v = \frac{\dot{m}}{\rho_0 A_s} \quad (8)$$

Experimental data related to this subject for fire temperatures can be found elsewhere /6.10/.

6.5 MEASUREMENT OF AIR FLOW

6.5.1 Principles of flow measurement

Air volumetric flow can be measured with a sensor or a flow constrictor permanently installed in the air duct, or by determining the local flow rate in the cross-section of the duct with a flow sond or anemometer.

A permanently installed flow measurement can be used in test set-ups where the aim is to determine the total cooling air quantity blown through the device. In this case the test conditions must be arranged such that the air blown through the device is guided through the measurement sensor (Figure 23). When sizing the fan the increase of pressure loss caused by this test set-up must be accounted for.

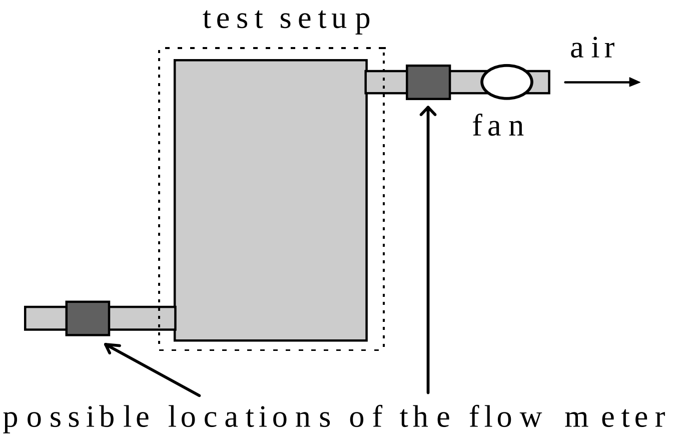


Figure 23. Possible locations for a flow meter permanently installed in the flow duct.

Measurement sensors and flow constrictors permanently installed in the air duct are continuously operating measurement methods, in which the measurement result can be obtained either in an analogue or electrical format. Continuously operating air quantity measurement devices installed thus in the air duct include the rotameter, turbine meter, thermal mass flow meters, vortex meters and different flow constrictors.

Local air velocities and velocity distributions can be measured from the flow duct or inside the component cabinet with a flow sond or anemometer. When the total air quantity flowing through the test set-up is to be determined, the average velocity is calculated from local velocity values measured at several locations of the flow duct cross-section. From the product of the average velocity and the flow cross-section one obtains the volumetric flow rate of the fluid flowing in the duct. A rotary vane, hot wire or thermal anemometer can be used as an flow sond. When the speed of flow is ≥ 3 m/s a static Pitot tube can be used as a flow sond.

Local, accurate values of the flow rate and direction in the flow duct can be obtained with more advanced measurement methods, such as the ultrasonic flowmeter, hot wire anemometry or laser Doppler anemometry. However, the measurement equipment required is expensive and often requires special test set-ups and good expertise. The above mentioned measurement equipment and accompanying service are available at research institutes, universities and technical universities /6.11/.

When investigating the internal flow distribution of the device under test, visual observation methods can be used such as signal smoke, fine powder and threads.

Table 3. 1996 price levels in Finland for some measurement devices for volumetric flow, velocity and pressure difference.

5000 mk ➥	10 kmk ➥	20 kmk ➥	40 kmk ➥	50 kmk ➥	over 100 kmk ➥
permanetly installed meters					
➥ rotameter					
➥ thermal mass flowmeter					
➥ vortex meter					
	➥ turbine meter + amplifier				
	➥vortex meter, pressure and temperature compensation				
local quantity meters					
	➥ multi-purpose meter for ventilation applications (measured quantities: w→0,2 m/s, temperature, humidity, pressure difference, memory for data storage)				
➥ thermal anemometer + display (direction dependent, w→0,2 m/s)					
	➥ thermal anemometer + display (direction independent, w→0,05 m/s)				
➥ rotary vane anemometer (w→0,3 m/s)					
		➥ hot wire anemometer, pressure and humidity compensation (w→ 0,1 m/s)			
					➥ hot wire anemometer, laser Doppler anemometer, velocity measurement based on ultrasonics, where 2 and 3 velocity components, direction and length can be measured
differential pressure meters4:					
	➥ precision micro manometer				
➥ capacitive pressure difference meter					

6.5.2 Factors affecting the selection of the measurement method

Before selection of the air quantity measurement method and measurement sensor, it is important to inquire what kind of device is to be studied and to estimate as accurately as possible the air quantity to be measured.

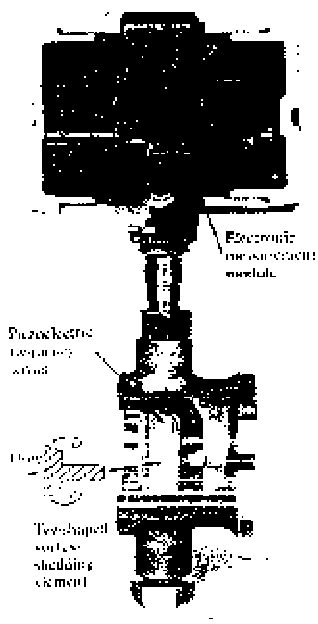
Factors affecting the choice of measurement sensor include the price of the sensor, the required accuracy, and the measurement location and its size. When selecting the measurement device the sensor measurement range must be considered, because a sensor with a wide measurement range or working at the extreme of its range has poor accuracy. The measurement sensor must be installed and operated following the respective manuals. When choosing the location of the measurement sensor, requirements for safety distances must be adhered to. Price levels in 1996 in Finland for different types of measuring equipment are listed in Table 3. The price information and minimum velocities shown in the table are gathered from product data sheets; therefore the values are indicative only and must always be confirmed for the respective device.

6.5.3 Permanently installed volumetric flow meters

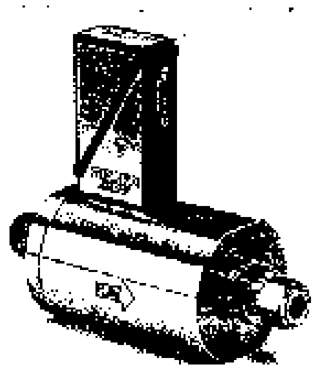
Meters permanently installed in the flow duct are appropriate for laboratory measurements since the total cooling air flow can be guided through the measurement sensor with a fan.

VORTEX EDDY FLOWMETER

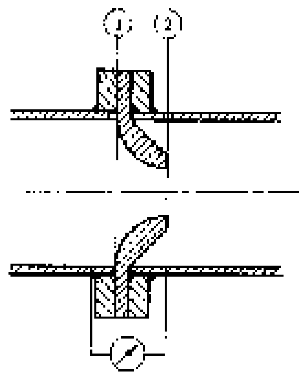
When a bluff object is placed in the flow, vortices are alternately shed in the flow downstream of the object. The shedding frequency of the vortex is directly proportional to the flow velocity. The shedding frequency is measured in the meter with a sensor based on either pressure, ultrasonic or heat transfer mechanisms. For accurate vortex meters the stated measurement inaccuracy is as small as ±0,3% in the wide measurement range of the sensor. The vortex meter is very sensitive to density and viscosity changes of the flowing fluid. Vortex meters equipped with pressure and temperature compensation are also available.



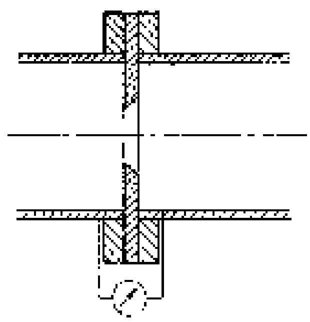
THERMAL MASS FLOWMETER



The working principle of the thermal mass flowmeter is based on heating of the flowing fluid and measurement of the flow temperature before and beyond the heating element. The temperature sensors measure the temperature difference caused by the heating, which is dependent on the flow velocity. There is a pressure and temperature compensation in the mass flow meter, therefore the pressure and temperature of the gas do not affect the measurement accuracy and the signal produced by the sensor is relatively accurate. The smallest measurement range of available mass flowmeters is 0,1...5 ml/min whereas the largest range is 25...1000 dm^3/min. The stated measurement inaccuracy for the meters is ± 1 % and repeatability ± 0,2 % from full scale reading.



ORIFICE, FLOW NOZZLE



The volumetric flow of air in a circular tube can be measured with a flow constrictor permanently installed in the flow tube. The velocity increases at the constricting location because of the reduced cross-section, and the pressure drops. The volumetric flow is determined from the measured differential pressure between the normal tube cross-section and the constricted cross-section. The constrictor also causes a permanent pressure loss, which must be considered in the design of the measurement system. An orifice or a flow nozzle, presented in the standard:

> SFS-ISO 5167 (1995) Measurement of fluid flow by means of pressure differential devices. Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full. 107 p. (or DIN 1952).

can be used as the flow constrictor. The inaccuracy of measurement sensors fabricated according to the standards is ± 2…4 %.

The differential pressure is measured from the flow constrictor (chapter 6.6), and from this pressure the volumetric flow of the gas flowing through the constrictor is calculated according to the standard. The measurement method for the differential pressure, the location of the measurement device in the flow tube, and the required safety distances are presented in the standard.

A measurement orifice is used when the flow tube is 50...1000 mm and the range of the orifice ratio is 0,05...0,64 (the ratio of the diameter of the orifice constrictor to the diameter of the flow tube). The measurement orifice is relatively accurate, but a fairly large permanent pressure loss is produced. A flow nozzle is used when the tube diameter is 50...500 mm and the orifice ratio 0,1...0,64.

OTHER PERMANENTLY INSTALLED VOLUMETRIC FLOW MEASUREMENT DEVICES

In the air volumetric flow measurement of air conditioning devices, different meters are installed in the flow duct (e.g. flow nozzle). Usually these devices measure the differential pressure, from which using the curvature or table provided by the manufacturer the air quantity flowing through the device is determined. These measurement sensors are often inexpensive but require calibration prior to use as well as a good differential pressure meter. The measurement inaccuracy is about ± 5 %.

OTHER VOLUMETRIC FLOW MEASUREMENT DEVICES

Rotameter

The simplest continuously operating air volumetric flow meter is the rotameter. This is a vertical tapered measurement tube in which a specially formed floating body (float) sits in an equilibrium position depending on the air flow entering the measurement tube from below. The rotameter tube is fabricated of glass or plastic on which a measurement scale is marked. The volumetric flow of the gas flowing through the meter is determined by the position of the float with respect to the scale.

The measurement range of rotameters used for determining air volumetric flow is 0,1 dm^3/min...100 m^3/h and the measurement inaccuracy ± 1...10 %. The rotameter measurement accuracy is affected by the pressure and temperature of the gas flowing through the meter. Although the measurement result can be converted to electrical format this multiplies the cost of the instrument. The rotameter is one of the least expensive volumetric flow measurement devices available.

Turbine meter

The turbine meter is installed in the flow duct. The air flowing through the sensor rotates the turbine and the rotation speed of the turbine is directly proportional to the air flow rate through the sensor. The signal obtained from the turbine meter is a frequency signal, which can be converted to a current signal with a transducer. Turbine meters are usually factory calibrated. They are available starting from a measurement range of 0,36... 3,6 dm^3/min to the range 24...240 dm^3/min.

The inaccuracy of the meter notified by the suppliers is ± 1 % for linearity and ± 0,1 % for repeatability. In the low range of the turbine meter´s operating region the measurement error is large, because friction strongly affects the rotation of the turbine at low flow velocities. The measurement accuracy of the turbine meter is further affected by the pressure and temperature of the gas. The safety distances required by the meter must be considered in its installation.

6.5.4 Measurement of local flow velocity

The velocity distribution of air flowing in a tube or channel depends on the fluid quantity flowing in the tube or channel and the cross-sectional area of the flow. In undisturbed laminar flow the velocity profile is of parabolic shape, attaining maximum velocity in the middle of the channel and reducing to zero at the walls. The velocity profile of turbulent flow is blunter, being fairly uniform at the centre and approaching zero at the walls.

Owing to the non-uniform velocity distribution the measurement is performed as a so-called multi-point procedure. The measurement cross-section should be perpendicular to the main flow direction and the velocity distribution should be as uniform as possible throughout the cross-section of the flow tube. The parallelness of streamlines and a uniform velocity distribution require sufficient safety distances before and beyond the measurement location.

When velocities or velocity distributions are to be determined in cabinets containing components, it must be considered when selecting the sensor that the flow contains many eddies, that accurate determination of flow directions is hard, and that local velocities can be very small. In this case good measurement accuracy at low flow speeds is required from the measurement sensor, and the properties of the sensor must be such that the measurement is independent of flow direction.

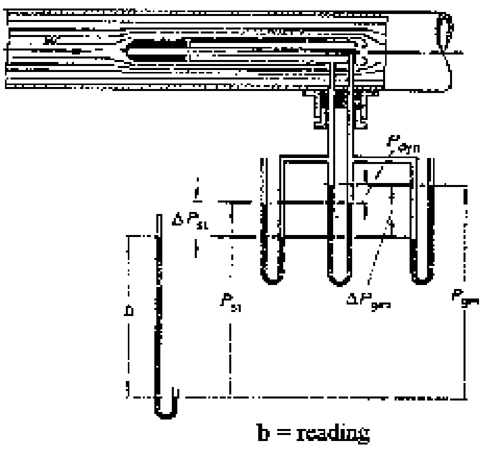
PITOT STATIC TUBES

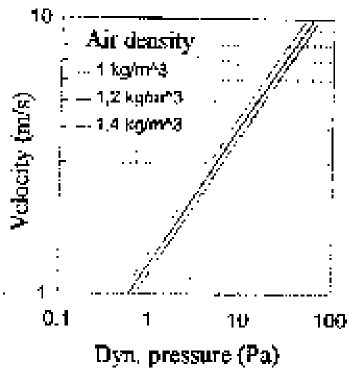
The Pitot static, i.e. the Prandtl tube, can be used for measurement of gas velocity in a channel or tube. The impact tube, bent at right angles, contains a hole in its hemispherical end, which is placed facing the direction of flow. The total pressure (p_{tot}) prevailing in the flow duct is measured from the hole. The Pitot static tube is equipped with holes along its side perpendicular to the direction of flow. The static pressure (p_{stat}) prevailing in the flow duct is measured from these slots. The dynamic pressure prevailing in the flow duct is obtained from the difference between the total pressure and the static pressure ($p_{dyn} = p_{tot} - p_{staat}$). The pressure difference between the total pressure and the static pressure is measured with a differential pressure meter (chapter 6.6).

The volumetric flow of air in the ducts can be determined with a Pitot static tube as described in the standard:

> SFS 5512 (1989) Air conditioning. Measurements of air flows and pressure conditions in air conditionings systems. 11 p.

The number and location of measurement points in the duct cross-section and the required safety distances are defined in the standard for ducts of different shapes and sizes.





The local flow velocity at the measurement point is determined from the dynamic pressure reading of a differential pressure meter by

$$w = \sqrt{\frac{2\ p_{dyn}}{\rho}}$$

where ρ is the density of the fluid flowing in the duct (for air ρ≈1,2 kg/m^3, when p=1,013 bar and T=20 °C). The flow velocity corresponding to the measured dynamic pressure p_{dyn} is presented in the figure on page 80. As can be seen in figure, the measured differential pressures at low flow velocities are very small, which requires an accurate differential pressure meter. In practice the velocities measured with a Pitot static tube are larger than 3 m/s.

The volumetric flow rate of air flowing in the duct q_V (m^3/s) is given by

$$q_V = \overline{w} A$$

where A (m^2) is the cross-sectional area of the duct. The mass flow rate of air flowing in the duct q_m (kg/s) is given by

$$q_m = q_V \rho$$

where ρ (kg/m^3) is the density of air flowing in the duct.

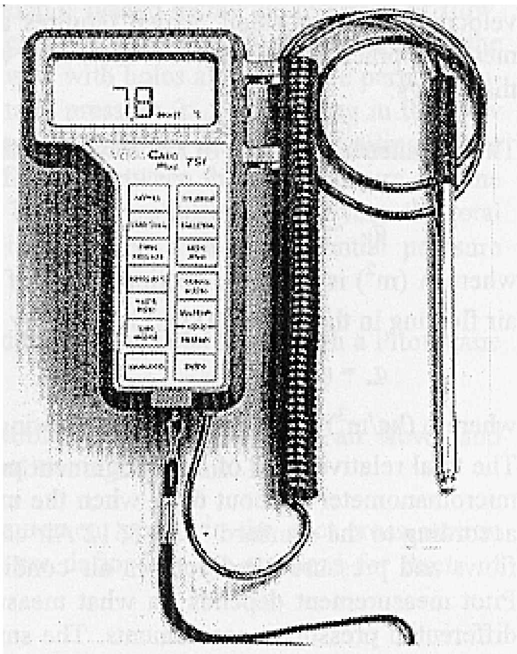
The total relative error of a measurement performed with a Pitot tube and a micromanometer is about 6 %, when the measurement has been performed according to the standard "SFS 5512 Air conditioning. Measurements of air flows and pressure conditions in air conditioning systems". The cost of a Pitot measurement depends on what measurement method is used for the differential pressure measurements. The smallest diameter of commercially available Pitot tubes is about 2,3 mm.

HOT WIRE AND HOT MEMBRANE ANEMOMETER AND THERMISTOR SENSOR

The working principle of the hot wire and hot membrane anemometer and the thermistor sensor is based on measurement of flow-induced cooling. The sensors function on the principle of either constant temperature or constant power. With the hot wire anemometer an electrically heated metallic wire is placed in the gas flow, cools the wire more efficiently the faster the flow velocity.

The form of the sensor used in the measurement varies according to the application. Thin wire sensors are often used to measure turbulence in fast gas flows. Spherical thermistor sensors are used to measure slow air flows in rooms. Both sensor types are direction sensitive, in other words the angle of attack between the sensor and flow affects the velocity measurement result and furthermore both are affected by self-convection. Self-convection causes measurement errors especially at small flow velocities.

In cases where the flow direction is not well known, direction insensitive sensors can be used. Instead of easily damaged wire sensors, more strongly constructed average velocity sensors based on the same working principle can be used. Thermistor sensors are of spherical shape



with a diameter of a few millimeters. The working principle of thermistor sensors is also based on the cooling effect of the flow. Thermistors are not very stable and require regular calibration.

The air flow quantity can be determined with the multi-purpose meter shown in the figure. The device may include a data logger with which the mean parameter values from various points can be measured. Quantities measurable with the meter and its properties are based on hot wire anemometer measurement.

- velocity measurement 0,15...50 m/s, inaccuracy about 2,5 % of reading
- differential pressure measurement -2500...+2500 Pa, inaccuracy about 0,5 % of reading
- air temperature measurement (-10...+60 °C, inaccuracy about 0,3 °C)
- relative humidity (5...95 %, inaccuracy about 3 % RH).

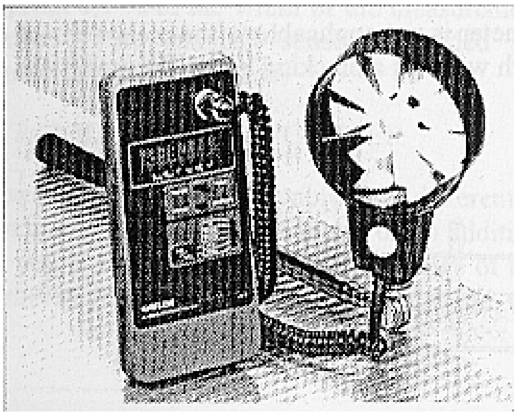
The device can include a built-in data logger, which can be used to determine an average value for a quantity measured at different measurement points. In the more expensive hot wire anemometers (20000 - 30000 mk) the measurement accuracy for measurement of flow velocities below 0,5 m/s is significantly improved.

VANE ANEMOMETER

The vane anemometer is a device containing a rotating vane in a cylindrical housing. The device is placed in the flow so that the longitudinal axis is parallel with the velocity. The forces on the vane due to components of flow along the perimeter of the vane cause the vane to rotate.

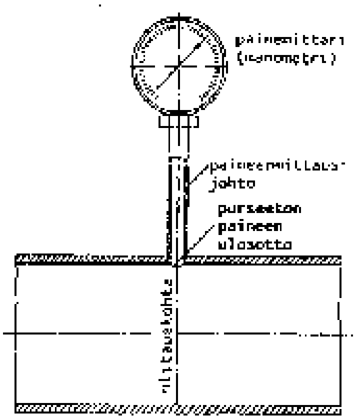
Although the bearings of the vane are made as frictionless as possible, friction forces do exist, one result of which is that the rotating speed at small flow velocities (range 0,2…0,5 m/s, where 0,2 m/s is the typical starting speed of the vane) is not directly proportional to the flow velocity. The manufacturer supplies correction curves or tables, obtained from calib-

ration measurements,



giving the correction factors. The measurement range of vane anemometers is 0,5...30 m/s and the measurement inaccuracy 1...5 %. The physical size of commercially available vane anemometers is 10…150 mm.

6.6 PRESSURE AND DIFFERENTIAL PRESSURE

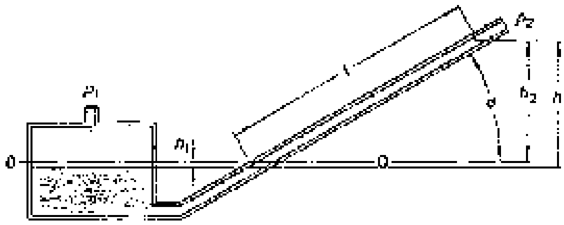


A measurement system for pressure and differential pressure consists of a pressure or differential pressure meter, measurement connections and a measurement hole. The pressure measured from the flow duct or measurement sensor is transmitted from the measurement hole through measurement leads to the measurement device. Many measurement methods for volumetric and mass flow rate are based on measurement of differential pressure. Often the measured pressure differences are very small, which sets special re-quirements for the resolution and measurement accuracy of the differential pressure measurement sensor.

In the measurement of pressure or differential pressure it is important that the measurement connections between the flow duct and the measurement device are correctly designed and built. There are detailed guidelines in the literature /6.7/ and standards concerning the location, size and form of the measurement hole in the duct to be measured and concerning the length and cross-section of the measurement connections. The measurement hole must be free from grit. The measurement of pressure or differential pressure can be performed with a mechanical, electrical or liquid tube manometer.

LIQUID MANOMETER

The cheapest alternative for differential pressure measurement is the U-tube manometer. Here a liquid tube is filled with a blocking substance, such as water, which is heavier than the measured substance (gas). The U-tube manometer is not applicable to the measurement of small pressure differences. With water as a blocking liquid the sensitivity of the meter is 0,05 mm/Pa.



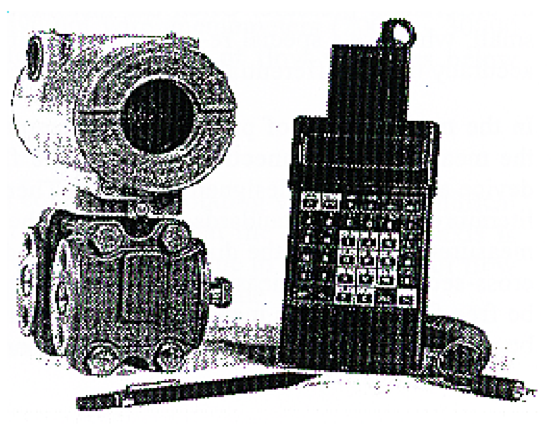
In the measurement of small pressure differences a more accurate measurement result is obtained with a Prandtl manometer or a variant of it, the tilted manometer whose sensistivity and readout accuracy can be altered by changing the inclination. From the height difference of the liquid column and the density of the liquid used in the manometer, the differential pressure can be determined from the relation

$$\Delta p = p_1 - p_2 = \rho g l \sin \alpha$$

where ρ is the density of the blocking liquid, g is the acceleration of gravity (9,81 m/s^2), l is the height of the liquid column, and α is the inclination angle of the tube. The measurement range for a tilted manometer is 0...100 Pa.

ELECTRICAL DIFFERENTIAL PRESSURE SENSOR

The pressure acting on a differential pressure sensor causes a displacement proportional to the pressure. The displacement can be converted to an electric quantity by using a resistive, inductive or capacitive method. The capacitive differential pressure sensor is based on this measurement method.

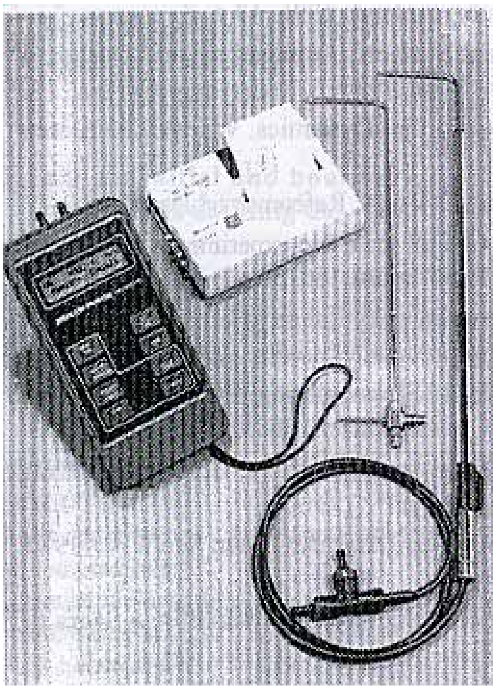


84

The signal obtained from a differential pressure meter is typically a 4...20 mA analogue signal, the lower limit of which is calibrated to correspond to zero differential pressure and the upper limit to the highest calibrated differential pressure value of the sensor. The inaccuracy of a differential pressure sensor is about 0,1 % of the width of the measurement range. The measurement range of the smallest sensors intended for differential pressure measurements is about 0...60 Pa.

THE MECHANICAL (ELECTRONIC) MICROMANOMETER

A micromanometer is an accurate and also easily vulnerable differential pressure meter. Micromanometers are available with displays or, in addition to the display, with an electric output signal. The measurement range of the battery powered manometer shown in the figure is 0...3500 Pa and the inaccuracy 1% of the reading.



REFERENCES TO CHAPTER 6

6.1. Moffat, Robert, J. Experimental Methods for Heat Transfer Measurements in Electronic Systems. Helsinki. Stanford University, Moffat Thermosciences, Inc. and Flomerics Limited, 1996. 54 p.

6.2. KOTEL ry. Mittaustekniikka elektroniikan lämpösuunnittelussa. Seminar. Oulu, Finland, 1996.

6.3. Farina, Dino, J. Making surface temperature measurements using liquide crystal thermography. Electronics Cooling 1995, vol 1, no. 2, October, pp. 10 - 15.

6.4. Parsley, M. The Hallcrest Handbook of Thermochromic Liquid Crystal Technology. Hallcrest, Dorset, United Kingdom, 1991. P. 36.

6.5. Tien, C.L., Chan, C. K., Cunnington, G. R. Infrared Radiation of Thin Plastic Films. Journal of Heat Transfer 1972, February, pp. 41 - 45.

6.6. Keski-Rahkonen, O. Ilman lämpötilan mittaaminen elektroniikkalaitteessa. KOTEL seminar. Oulu, Finland, 1996. 13 p.

6.7. Doebelin, E, O. Measurement Systems, Applications and Design. 4th Edition. McGraw-Hill, New York, 1990.

6.8. Drysdale, D. An Introduction to Fire Dynamics. Wiley, Chichester, 1985.

6.9. IEC 584-1. 1995. Thermocouples Part 1: Reference tables. 155 p.

6.10. Mangs, J., Keski-Rahkonen, O. Full scale fire experiments for instrument cabinets. Espoo, 1994. VTT Publications 186. 50 p. + app. 37 p.

6.11. Saarenrinne, P. Virtausmittausten nykytilanne ja kehittäminen. Tampere 1995. TTKK/Energia- ja prosessitekniikka. Report 108. 54 p.

6.12. Benard, C. J. Handbook of Fluid Flowmetering. England. The Trade & Technical Press Limited Crown House, 1988.

6.13. Michalski, L. Temperature Measurement. Wiley, Chichester, 1991. 514 p.

6.14. Paine ja virtaus. Helsinki. Suomen Säätöteknillinen Seura ry., 1981. Julkaisu n:o 4.

6.15. Lämpötilan mittaukset. Helsinki. Suomen Säätöteknillinen Seura ry., 1981. Julkaisu n:o 3.

6.16. Sirén, K. Ilmastointitekniikan mittaukset. Helsinki. Tietonova Oy, 1995.

6.17. Halko, P., Härkönen, S., Lähteenmäki, I. & Välimaa, T. Teollisuuden mittaustekniikka. Perusmittaukset. Helsinki. Ammattikasvatushallitus, 1990.

APPENDIX 1
PRINCIPLES OF THERMAL DESIGN

PHYSICAL BASIS OF THERMAL DESING

Figure 1 shows the basic equations that mathematically describe the thermal behaviour of the devices and the thermal and fluid mechanical behaviour of the fluid field. In the figure, the system separated from its environment by a control surface can be a component, a component board, a subrack, or a cabinet. The methods of thermal design include numerical and analytical calculations and empirical measurements.

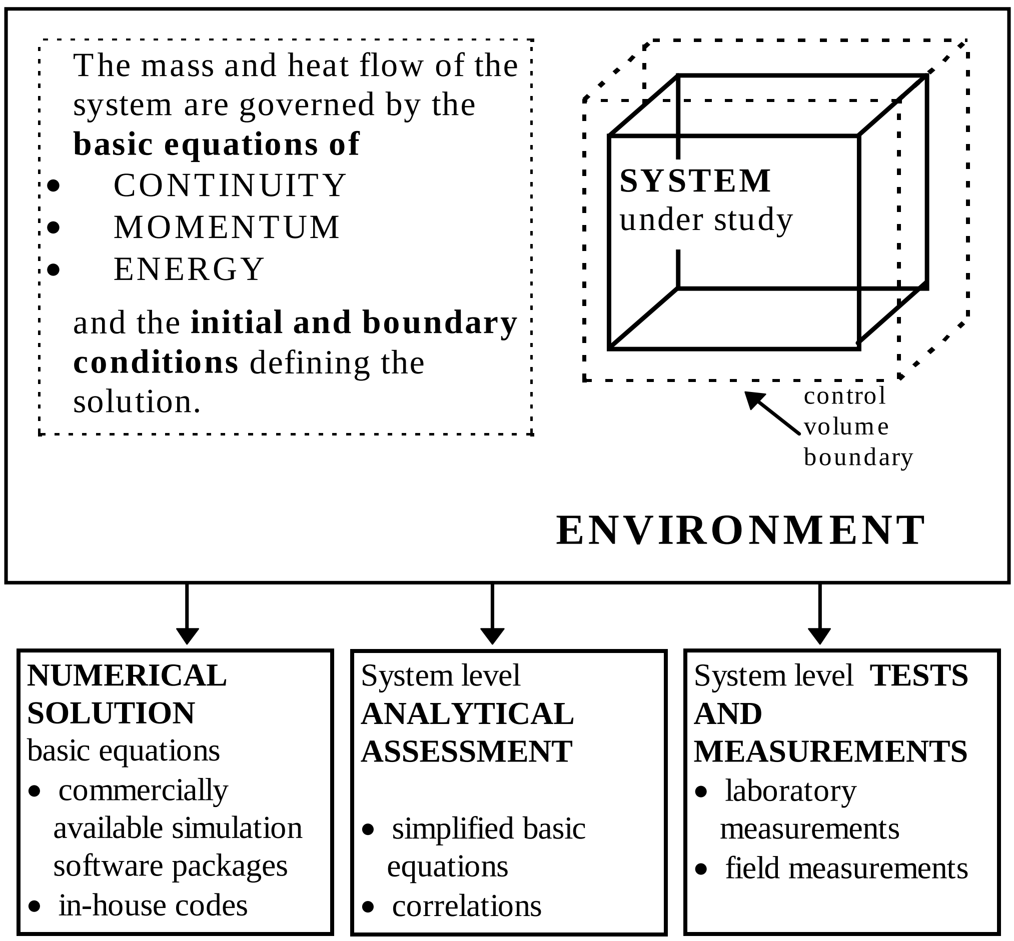


Figure 1. The physical basis of thermal design.

Both the analytical examination and numerical computing using simulation software are based on basic equations. In manual calculation, remarkable simplifications are needed in these equations. The simplifying assumptions are determined by the system and situation under examination.

In simulation programs, various numerical methods and calculation models of turbulent flow are used to solve the above-mentioned basic equations, hence the variation in correctness and accuracy of the results.

In both analytical and numerical calculation, in addition to the basic equations the **initial and boundary conditions** are essential for their solution.

BASIC EQUATIONS

The derivation of the basic equations is presented in various books on fluid mechanics and heat transfer /e.g. 1-4/. The derivation of the equations begins with the examination of a differentially small control volume (cv) by adapting the three basic laws of conservation of mass, momentum, and energy at different moments (non-stationary state). The greater the frequency of the examination and the smaller the elements (control volumes) into which the volume is divided, the more accurate the modelling. This is the way to observe fast changes and small local turbulences in the fluid field.

Five basic equations are needed to describe a one-phase, three-dimensional control volume; one continuity equation, three momentum equations (three dimensions), and one energy equation.

The continuity equation, or the equilibrium equation of mass, describes the mass change of the control volume with time ($\overline{V}$ resultant speed) /1, 2/:

$$\frac{D\rho}{Dt} + \rho \, div \, \overline{V} = 0 \qquad (1)$$

The **momentum equation**, or the equilibrium equation of forces, is used to determine the forces affecting the acceleration of the control volume mass. The forces affecting the momentum of the control volume mass include both body and surface forces. Body forces affecting the control volume mass include gravitational and centrifugal forces, and magnetic and electric fields. Surface forces affecting on the surface of the control volume are pressure, shear stresses on tangential direction and normal stresses. For viscous, Newtonian flows, the momentum equation — generally called the Navier-Stokes equation — can be expressed in its general form /1, 2/:

$$\rho\frac{Du}{Dt}=\rho\bar{g}_x-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left[\mu(2\frac{\partial u}{\partial x}-\frac{2}{3}div\bar{V})\right]+\frac{\partial}{\partial y}\left[\mu(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})\right]+\frac{\partial}{\partial z}\left[\mu(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z})\right]$$

$$\rho\frac{Dv}{Dt}=\rho\overline{g_y}-\frac{\partial p}{\partial y}+\frac{\partial}{\partial y}\left[\mu(2\frac{\partial v}{\partial y}-\frac{2}{3}div\bar{V})\right]+\frac{\partial}{\partial z}\left[\mu(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y})\right]+\frac{\partial}{\partial x}\left[\mu(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})\right] \qquad (2)$$

$$\rho\frac{Dw}{Dt}=\rho\overline{g_z}-\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}\left[\mu(2\frac{\partial w}{\partial z}-\frac{2}{3}div\bar{V})\right]+\frac{\partial}{\partial x}\left[\mu(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z})\right]+\frac{\partial}{\partial y}\left[\mu(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y})\right]$$

When there is no heat transfer within the examined system (isothermal system), the fluid mechanical behaviour of the control volume — the velocity and pressure distributions — can be determined on the basis of the continuity equation and momentum equations. If there are temperature differences in the system examined resulting in heat transfer, the energy equation is also needed to calculate the temperature distributions and temperature dependant properties.

The **energy equation** of the control volume can be determined using the principle of energy equilibrium (conservation of energy) /1, 2/

$$\rho\,\frac{Dh}{Dt} = \frac{Dp}{Dt} + div\,(k\,gradT) + \Phi \qquad (3)$$

The term on the left of the equation is the total differential of the control volume enthalpy with time. The factors affecting the enthalpy of the control volume are the total differential of pressure, the heat conduction on the control surface, and the conversion of the kinetic energy to thermal energy due to friction (increase in entropy) which is taken into account by a dissipation factor (Φ).

The basic equations are very complex and mostly impossible to solve analytically, which means that they cannot be used directly in analytical calculation of differentially small control volumes. In rough calculations at component, component board, and cabinet levels, slightly simplified basic equations are very practicable. Instead of detailed information on temperature and velocity distribution, it is possible to achieve an idea of the total energy balance of the examined system and comparable information with measurement results. The result of the numerical method and its accuracy depends on the solution method. The accuracy of the calculation (in other words, the finesse of the volume´s space and time division) is determined by the calculation capacity, the calculation time, and the simulation software. Generally, it can be said that the smaller the control volumes, the greater the calculation capacity needed (powerful computer) and the more detailed information obtained about the volume examined.

ANALYTICAL EXAMINATION - ENERGY BALANCES AND BOUNDARY CONDITIONS

In the thermal design of electronic devices, it is essential to know the basic mechanisms and models of heat and mass transfer and flow dynamics. The behaviour of the system can be determined from the basic equations. Since analytical calculation of the basic equations is difficult and to some extent impossible, some simplifications are needed in the manual thermal balance examination. The different types of *heat transfer* and the critical factors affecting the cooling efficiency must be known. In the cooling of electronic devices, all the basic mechanisms of heat transfer occur — heat conduction, convection and heat radiation.

The heat transfer between the coolant and the surface of the component, printed wiring board or subrack/cabinet to be cooled can be intensified by successful *fluid dynamic* design. From the fluid dynamic point of view, attention should be paid to the structure of the housing and the coolant air holes as well as to the location and position of the component boards within the housing. In addition to these, the location of the components on the printed wiring board affects the cooling efficiency.

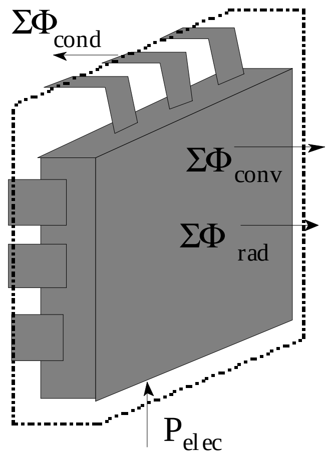
In air cooled devices, in which cooling takes place through either free or forced convection and radiative heat transfer, the *mass transfer* is often restricted to condensation or evaporation of the coolant air moisture on solid surfaces and to possible diffusion of the moisture to structures and devices.

The **boundary conditions** used in thermal design — the initial values of the design — are taken into account as boundary conditions also in the verification. Boundary conditions to be considered are environmental conditions as a function of time: temperature (temperature differences), heat radiation, air pressure, moisture and dirt. In the verification, the examination of energy balances can be done on different levels. Energy flows and mass flows resulting in enthalpy flows move across the control surfaces.

A) Energy balance of a single **component**

Energy flows include the *electrical power* supplied to the component, the *heat convection* and *radiation* between the component and its environment, and the *heat conduction* between the component and the printed board. The proportions of different heat transfer types and the quantity of heat flows are affected by:

- the structure, material and properties of the components
- the connection of the components on the printed board, number of leads, structure and material of leads
- an extra finned heat sink on top of the component (fins)
- the contact resistance between two solid surfaces (interfaces).



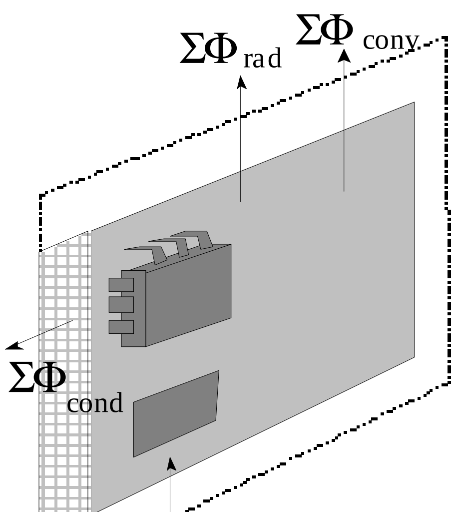
Heat convection is affected by the temperature and velocity of the surrounding air.

Heat radiation is affected by the temperatures of the surrounding surfaces.

B) Energy balance of a **component board**

Energy flows are the electrical power supplied to the component board, the heat convection and radiation between the component plate and the environment, and the heat conduction between the component plate and the subrack. The quantities and proportions of heat flows are affected by:

- the material and structure of the printed wiring board
- the structure, quality and quantity of the components on the board
- the connection of the board to the subrack, the conduction routes.



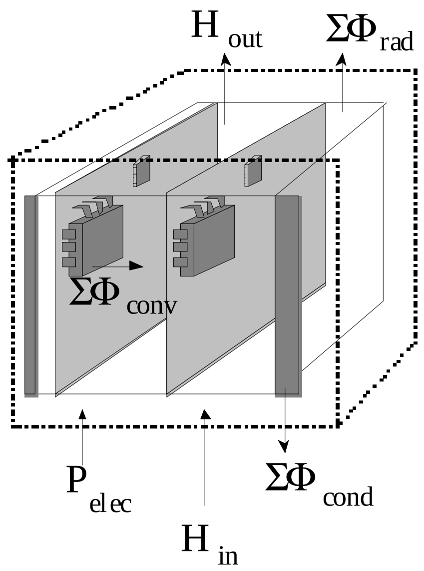
C*onvection* is affected by the temperature and velocity of the surrounding air.

Heat radiation is affected by the temperatures and radiative properties of the board and surrounding surfaces.

C) Energy balance of the **subrack**

Energy flows are the *electrical power* supplied to the subrack level, the *heat convection* between the component plates and the surrounding air and *heat radiation* between the boards within the subrack and between the solid surface surrounding the subrack and the component plates. Heat can also be transferred by *conduction* between the subrack connecting to the device cabinet. The quantities and proportions of the *heat flows* are affected by:

- the mutual location and position of the component boards in the subrack
- the structure, size, location, and material of the subrack, the connection of the boards to the subrack and the connection of the subrack to the cabinet
- quantity and routes of air flow through the subrack
- the temperature and velocity of the surrounding air affecting heat *convection*, and the temperatures and radiative properties of the surrounding surfaces affecting *heat radiation*.

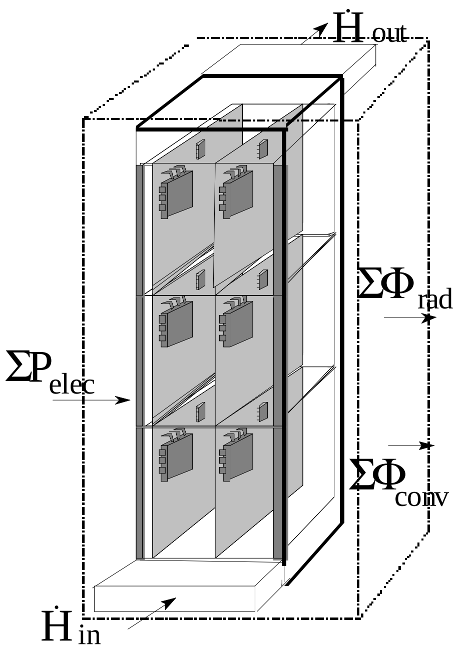


D) Energy balance of the **cabinet**

Energy flows are the electrical power supplied to the cabinet, the heat convection and radiation between the outer surface of the cabinet and the environment, and the enthalpy flow of the cooling air. The quantities and proportions are affected by:

- the structure and material of the inner surfaces of the cabinet
- the quantity, temperature and moisture of the incoming air.

The temperature and velocity of the surrounding air affect the *convection*, and the temperatures and radiative properties of the cabinet/housing and the surrounding surfaces and objects (e.g. the sun) affect the *radiative* heat transfer.



THE BASIC MECHANISMS OF HEAT TRANSFER

In the following, the basic mechanisms of heat transfer are discussed generally. Attention is paid to factors affecting the quantity of heat flow — the cooling efficiency — in different types of heat transfer. The basic theory of heat transfer is described in the literature /e.g. 3, 4/.

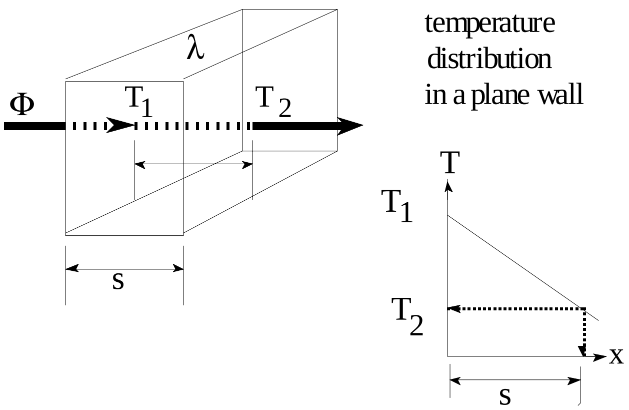
Heat conduction

Conduction is the transfer of energy due to interactions between molecules, atoms, ions and crystals which vibrate and collide. Conduction can take place in solids, gases and liquids. In gases and liquids, temperature differences create density differences resulting in mass transfer, in other words free convection, in addition to pure heat conduction.

When considering an infinitesimally small control volume through the control surface, of which heat energy is transferred only by conduction, the energy equation (3) can be expressed in x, y, z-coordination as /3/:

$$\rho\, c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) + \phi''' \qquad (4)$$

In addition to the equation above, initial and boundary conditions are also needed to solve the temperature distribution of the volume. The equation above can be further simplified by considering a stationary, one-dimensional situation where no heat is generated within the volume.



The heat transfer rate Φ (W) through the surface, or the heat transfer rate per unit surface Φ“ (W/m^2) can be calculated from the equation (5):

λ = thermal conductivity (W/m K)
s = thickness of the layer (m),
A = cross-sectional area (m^2)
R = **thermal resistance** (`K/W)
R" = thermal resistance on the cross-sectional area (K m^2/W)
T = T_2 - T_1 temperature difference (K),
T_1 is the temperature of the warmer surface and T_2 that of the colder surface.

$$\phi = \frac{\lambda}{s} A \, \Delta T = \frac{1}{R} \Delta T$$

$$R = \frac{s}{\lambda A} \qquad (5)$$

$$\phi'' = \frac{\lambda}{s} \Delta T = \frac{1}{R''} \Delta T$$

$$R'' = \frac{s}{\lambda}$$

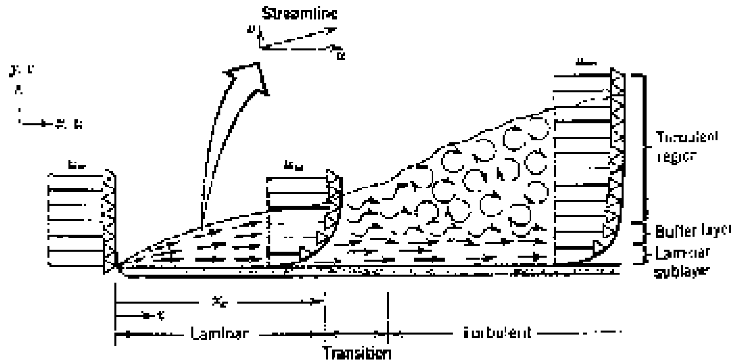
The smaller the thermal resistance R”, the greater the heat flux (Φ“) transferred by conduction due to the temperature difference. The thermal resistance is affected by the thermal conductivity (λ) and the thickness of the layer (s). The greater the thermal conductivity and the thinner the conduction layer, the smaller the thermal resistance and the greater the heat rate by conduction through the wall.

Heat transfer by convection

Heat convection means the transfer of thermal energy by fluid flow (liquid or gas) and especially the heat transfer between a solid surface and a moving fluid (liquid or gas) when these are at different temperatures. The convection heat transfer mode comprises two mechanisms; energy transfer by diffusion (the random motion of molecules) and by the bulk (the motion of fluid).

Convection heat transfer is classified according to the nature of the flow. In **free convection** the flow is induced by the buoyancy force, which arises from density differences caused by temperature variations in the fluid. The heavier fluid moves downward due to gravity, the lighter fluid moving upward. In **forced convection**, the fluid flow is generated by external forces, either with a fan or a pump. Thus a difference in density of the fluid causes a flow of material.

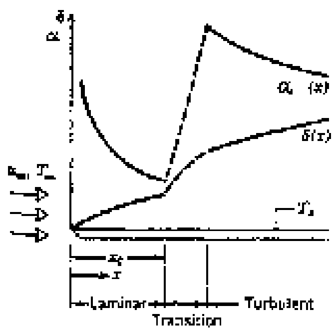
In the picture below, a boundary layer is formed in fluid flowing on a smooth surface (velocity and temperature boundary layer) in which the velocity and temperature of the fluid change from the surface values towards the values of free flow (potential flow). Beyond the collision point of the flow and plate, the velocity of the boundary layer is at first laminar, becoming totally turbulent beyond the transient zone. In laminar flow, the streamlines of the fluid are parallel and the heat is transferred through the laminar fluid layer — perpendicular to the direction of the surface — mainly by diffusion (conduction).



In the turbulent boundary layer,turbulence occurs in the fluid field, fluid is mixed, and heat transfer between the surface and the fluid is intensified. Instead of pure diffusion, the energy transferred by the fluid motion (convection) becomes the dominating form of heat transfer. Moreover, in turbulent flow there is a thin laminar boundary layer near the surface through which the heat between the surface and the fluid is transferred by diffusion. Because the laminar boundary layer is thin, its thermal resistance is low. The boundary layer begins to develop from the collision point of the flow and the solid surface. Initially the boundary layer is thin, becoming thicker in the flow direction. For heat transfer, the phase to be avoided is a thick laminar boundary layer in which the heat transfer between the surface and the fluid is minor.

The behaviour of the potential flow and boundary layer flow can be described with the basic equations (1), (2) and (3). In numerical calculation, the fluid field is divided into elements (control volumes) according to the accuracy desired, and the velocity, pressure and temperature distributions are calculated.

In the analytical examination, Newton´s law of cooling can be used to estimate approximately the heat transfer rate obtained by convection. In this equation, the average heat transfer coefficient can be determined using correlations. The picture represents the variation of the heat transfer coefficient α on various sections of the boundary layer δ.



According to Newton´s law of cooling, the heat transfer rate between the surface and the fluid can be calculated from the equations (6).

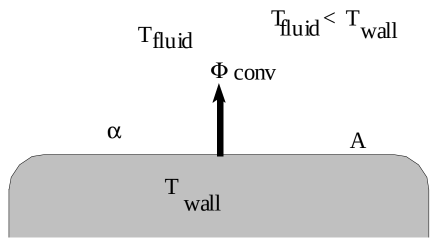
$$\phi = \alpha A \Delta T = \frac{1}{R}\Delta T$$

$$R = \frac{1}{\alpha A} \qquad (6)$$

$$\phi'' = \alpha \Delta T = \frac{1}{R''}\Delta T$$

$$R'' = \frac{1}{\alpha}$$

In the equation, α is the average heat transfer coefficient between the solid surface and the fluid (W/m^2K),
A is the thermal area (m^2),
R is the **thermal resistance** (K/W) and $\Delta T = T_{surface} - T_{fluid}$ is the temperature difference in which $T_{surface}$ is the temperature of the surface and T_{fluid} that of the surrounding free flow.



With a given temperature difference, the heat transfer rate by convection is greater the smaller the value of the thermal resistance R. A small thermal resistance can be achieved when the product of the heat transfer coefficient and the heat transfer surface area is great. It can be seen from the equation that when the heat transfer coefficient is small, the thermal resistance can be reduced by increasing the heat transfer area (fins).

When calculating heat transfer by convection, various dimensionless parameters can be used to determine the average heat transfer coefficient α. Parameters appropriate for free and forced convection in different flow situations are described in the literature /e.g. 3, 4/. The value of the heat transfer coefficient α is affected by the quantity of the mass flow, the properties of the fluid, and the geometry of the fluid passage. The properties of the fluid affecting heat transfer are viscosity, thermal conductivity, density, and specific heat.

Cooling efficiency can be influenced by the geometry of the devices and the fluid passages, both in free and forced convection. Attention should be paid when designing the cabinet to the form of the housing, the materials used, the quality of the surface, and the location of the cooling air holes. When installing component boards within the housing, attention should be paid to the position, form, and materials of the component boards and the mutual location of the component boards within the cabinet. The cooling of the components is affected by the size, the surface materials and the quality of the components, including the location of the components on the printed board. In cooling by free convection, the proportion of radiative heat transfer is remarkable.

Heat transfer by radiation

The energy of the radiation field is transported by electromagnetic waves and heat is transferred between surfaces with different temperatures so as to reduce the temperature difference. All surfaces radiate in proportion to their temperature (in fact as the fourth power) but the direction of the net heat transfer is from the warmer surface to the colder one.

Characteristic of radiation impinging on a surface is that part of it can be reflected from the surface (described by the reflection coefficient ρ), part of it may be absorbed by the surface (described by the absorptivity coefficient α), and part of it may be transmitted through the surface (described by the transmissivity coefficient τ). Because energy is conserved, the three coefficients are related:

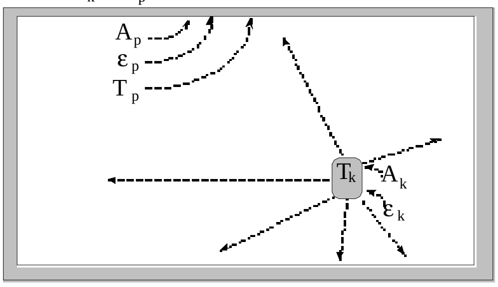
$$\rho + \alpha + \tau = 1 \qquad (7)$$

The distribution of radiation impinging on a surface depends on the surface´s properties. If a piece of matter (surface) is opaque to the incident radiation its transmissivity (τ) is zero. On well polished surfaces, the reflection coefficient is large, which means that most of the irradiation is reflected from the surface, while only a relatively small fraction is absorbed by the surface ($\alpha = 1 - \rho$, when transmissivity $\tau = 0$).

The emission of thermal radiation from the surface depends on the temperature and radiative properties of the surface. The parameter describing the radiative efficiency of the surface is the emissivity ε. For a perfect emitter (radiator), a blackbody, the emissivity value equals 1. The emissivity of the surface is a function of temperature, wavelength and radiation angle. The emissivities of different materials can be found in the literature.

In radiative heat transfer, the net heat transfer rate of radiation between two surfaces can be calculated with the equation

$$\phi = \frac{\sigma A_k (T_k^4 - T_p^4)}{\frac{1}{\varepsilon_k} + (\frac{A_k}{A_p})(\frac{1}{\varepsilon_p} - 1)} \qquad (8)$$

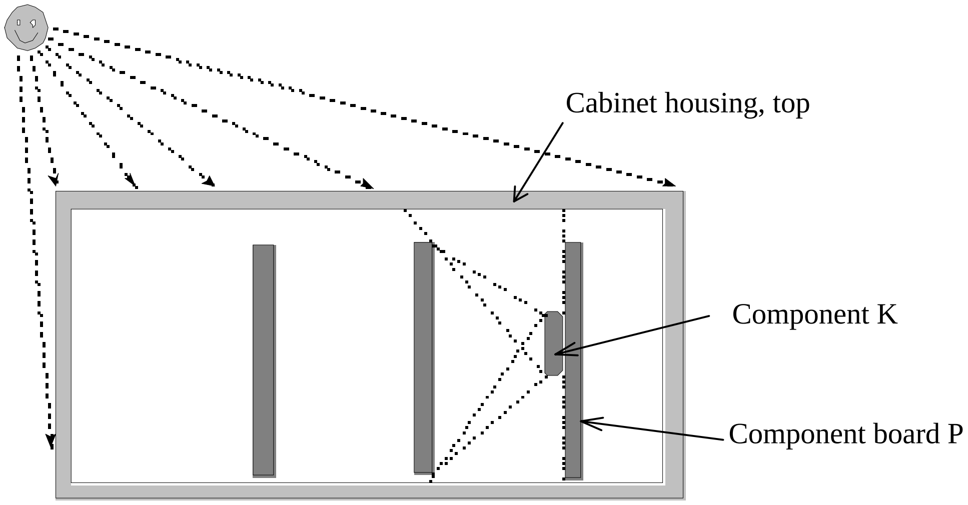


If the area of the object A_k is very small compared with the surrounding area, the relation A_k/A_y approaches zero, and the equation for the net rate of radiation heat transfer can be expressed as

$$\phi \approx \sigma A_k \varepsilon_k (T_k^4 - T_p^4) \qquad (9)$$

where the Stefan-Boltzmans constant is $\sigma = 5{,}67 \times 10^{-8}$ W/m^2K^4.

View factors are used to take into account how different surfaces "see" each other and to calculate the net radiation heat flow between them. Component K can "see" the upper surface of the housing with a view factor $F_{comp - housing, top}$. On the other hand, component K "sees" the next component board P with a view factor $F_{comp - board}$ and the lower surface of the housing with a view factor $F_{comp - housing, bottom}$.



The sum of the view factors equals one.

$$F_{comp -housing, top} + F_{comp - board} + F_{comp - housing, bottom} = 1 \qquad (10)$$

Radiative heat transfer occurs between each surface a component “sees” and the component itself. Every surface has a certain temperature and emissivity. The net thermal flow between component K and the surrounding surfaces can be expressed as

$$\phi \approx \Sigma(F_{k-i} \sigma \; A_k \;\; \varepsilon_k \;\; (T_k^4 \; - \; T_{pi}^4)) \tag{11}$$

The radiative heat transfer between two surfaces can be reduced with shields between them.

Radiative heat transfer affects the cooling of components when cooling is by free convection. The importance of radiative heat transfer is decreased when cooling is by forced convection.

REFERENCES TO APPENDIX 1

1. Schlichting, H. Boundary-Layer Theory. USA. McGraw-Hill Book Co. 1977.
2. White, F. M., Viscous fluid flow. Second ed. New York. McGraw-Hill Book Co. 1991.
3. Incropera & DeWitt, Fundamentals of Heat and MassTransfer. Third ed. 1990. John Wiley & Sons.
4. Holman, J. P., Heat Transfer. McGraw-Hill Book Co. 1989.