Small Form Factor Cooling Considerations for Intel® Processors and Chipsets

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1.0 Introduction

Small form factors are widely used for market segments such as industrial applications, consumer products, point of sales/information terminals, medical devices, communications, transportation, education terminals, traffic control and many more.

The continuing use of small form factors has brought opportunities to implement Intel's high-performance microprocessors and chipsets into embedded computer applications and build a thermal solution to effectively cool the board. This document provides considerations on implementing Intel® processors and chipsets into small form factors with these thermal solutions:

- Natural convection (fanless)
- Passive (with system airflow)
- Active

A small form factor can be characterized as: a system board that contains processor and chipset whose total board area is less than 300 cm^2. Many of these small form factor boards are placed in a chassis that contains multiple boards in a rack configuration, as the main board, or as a daughter-card/mezzanine-card.

There are multiple configurations that are available for small form factor boards, so the thermal solution will depend on which market segment the board is targeted at. Because of the many available configurations, there is no one standard thermal solution that applies to all small form factor boards.

Consideration and implementation of the recommendations in this document enable better thermal solutions, lower design time, and faster integration.

1.1. Cooling Intel's High-Performance Processors

The selection of processors and chipset relies heavily on current cooling capacities. The thermal solution design is greatly affected by the constraints imposed by the chassis configuration and system boundary conditions.

To meet the requirements of the market, these microprocessors must comply with these key requirements:

- Compactness in design
- Low power consumption
- An emphasis on high reliability

While small form factors have enormous potential for multiple market segments, the ability to cool high performance processors and chipsets can be the main limiting factor in designing a small form factor board. Planning the thermal solution early in the design cycle with the recommendations in this document will ensure development of an effective cooling solution.

2.0 Thermal Design Considerations for Small Form Factors

There are two categories of parameters that primarily influence thermal solution design:

- System boundary conditions
- Component characteristics.

Thermal solution design must address both of these issues.

2.1. System Boundary Conditions

The environmental parameters that influence thermal solution design are determined by the system and chassis configuration. System boundary conditions that influence thermal solution design include:

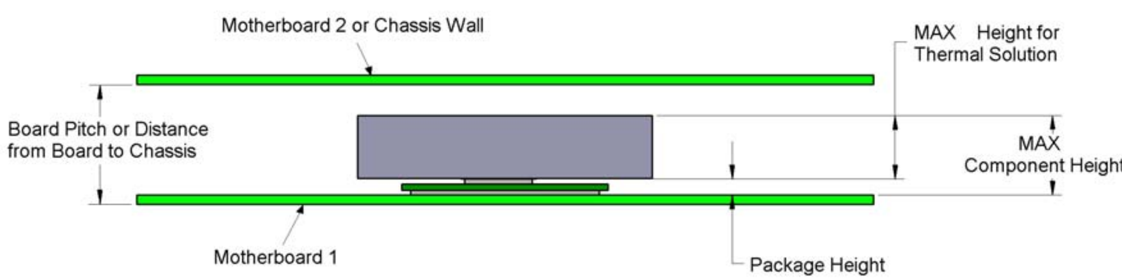
- Board dimensions
- Allowable height for the thermal solution
- Maximum local ambient temperature (T_{LA})
- System airflow

2.1.1. Board Size and Maximum Height

The size of the board is important to thermal solution design because it dictates what components can fit on the board and how large the thermal solution footprint can be. When designing a heatsink, there is a certain thermal solution volume that is needed to dissipate a given power. To accomplish the necessary volume, the thermal solution can either be taller or wider depending on the boundary conditions. It is important to note that a taller heatsink is more efficient than a wider one.

Figure 1 shows an example of what a typical mechanical stack-up of a processor in a small form factor would look like. When designing a thermal solution, it is important to consider aspects such as maximum component height and maximum height for the thermal solution. Exact dimensions for these heights can be found in the small form factor you are using, or in the applicable Processor Thermal Design Guide.

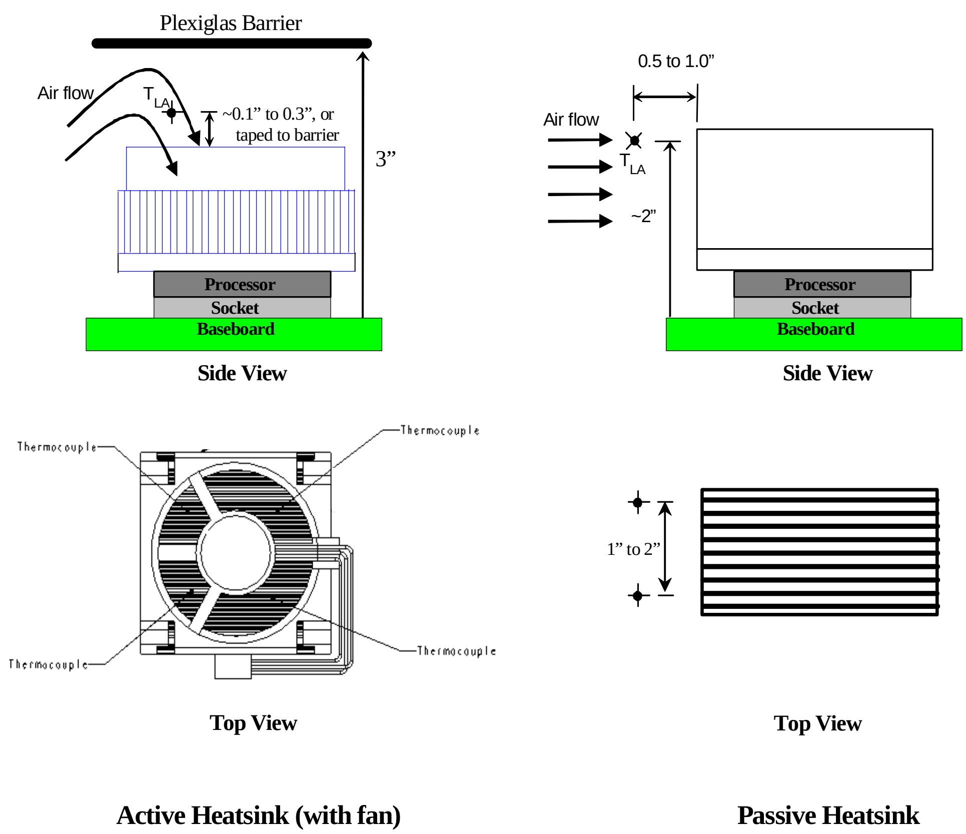
Figure 1. Typical Small Form Factor Mechanical Stack-Up



2.1.2. Local Ambient Temperature

The local ambient temperature (T_{LA}) is a significant influence towards cooling a processor and chipset in small form factors. The T_{LA} is defined as the local temperature measured approximately 1" upstream of the thermal solution in a passive system or directly above the fan of an active solution. The local ambient temperature includes the ambient temperature, plus any temperature rise due to other components in the system ($T_{LA} = T_A + T_{rise}$). The measurement location of T_{LA} is shown in Figure 2.

Figure 2. Local Ambient Temperature Location



The thermal resistance or Ψ (Psi) is calculated for a given thermal solution so that it may be compared to other thermal solutions in identical conditions. In any computer system it is necessary to calculate the required thermal resistance needed in order to keep the processor and chipset within their operating temperatures. The thermal solution must maintain the processor die at or below the specified junction temperature. The equation for calculating the junction-to-ambient thermal resistance is shown in Equation 1.

Equation 1: Junction-to-Ambient Thermal Resistance

$$\psi_{JA} = \frac{T_{J\max} - T_{LA}}{TDP}$$

Where:

Ψ_{JA} = junction-to-ambient thermal resistance in °C/W

T_{Jmax} = Maximum junction temperature of processor as specified by the datasheet in °C

T_{LA} = Maximum local ambient temperature in °C

TDP = Thermal Design Power in watts (W)

When calculating the required thermal resistance, the T_{LA} is important to determine the allowable temperature delta from the maximum operating environment to the component's maximum specification. It is important to know that lower Ψ_{JA} values require better thermal solutions and vice versa.

Typical T_{LA} values for small form factors range from 45-55 °C.

Example 1: Cooling an Intel® processor
The thermal solution needed to cool an Intel® processor with a T_{Jmax} of 100°C and a TDP of 10 W in a system with a T_{LA} = 50°C, would need to have a junction-to-ambient thermal resistance of:

$$\psi_{JA} = \frac{100 - 50}{10} = 5.0^{\circ} C / W$$

The thermal solution for this situation requires a thermal resistance less than or equal to 5.0°C/W to keep the component within specifications.

For more information on Intel® specifications for processors and chipsets, including thermal measurement methodologies, refer to the various product specific thermal design guides located at http://developer.intel.com/design/intarch/.

2.1.3. Airflow

There are three basic types of thermal solutions: passive, active, and natural convection.

Passive and active thermal solutions rely on airflow from an external device (fan) to remove the heat from the device.

Natural convection heatsinks do not rely on external airflow, only the movement of air caused by thermodynamics is used for convection.

Passive heatsinks are the most common type of thermal solutions in embedded and small form factors. Embedded computer systems have passive heatsinks attached to the computer chip(s), and the system fans supply airflow through the fins. The design of a passive heatsink is dependent on the amount of airflow that can be provided by the system. The more airflow, the better the heat transfer, resulting in a lower (better) thermal resistance of the heatsink. By providing more airflow, the size of the heatsink may be reduced in some cases. In general, most embedded systems and small form factors can provide airflow at a rate of 100-300 Linear Feet per Minute (LFM) at the heatsink. The measurement of this airflow is taken at the same points as T_{LA}, which is shown in figure 2 for passive heatsinks. The thermal solution for a small form factor should have the heatsink optimized for the amount of airflow provided.

Active fansinks are not as widely used in small form factors. This is due to the fact that they generally require more height than a passive solution and introduce reliability issues associated with the fan. Active fansinks are a good choice for systems that have the available height, due to better performance when compared to passive heatsinks. Fansinks generally have better performance because the impingement airflow removes heat more efficiently. The residual airflow that exits the fins is also beneficial for the surrounding components. Other heat dissipating devices located close to the processor usually use passive heatsinks and rely on the exhaust airflow from the active heatsink The type and amount of airflow provided by the system is an important factor and needs to be considered when designing thermal solutions for small form factors.

2.2. Component Characteristics

When designing a thermal solution for a small form factor board, consider the following:

- components (i.e., processor, chipset, memory)
- specifications
- placement in the system

The specifications for the components are important in thermal design because they determine how feasible it is to develop a thermal solution for a small form factor. The most important specifications are the maximum component temperature and the Thermal Design Power (TDP). Once all factors are considered, the solution should be optimized for the intended system.

2.2.1. Component Specifications

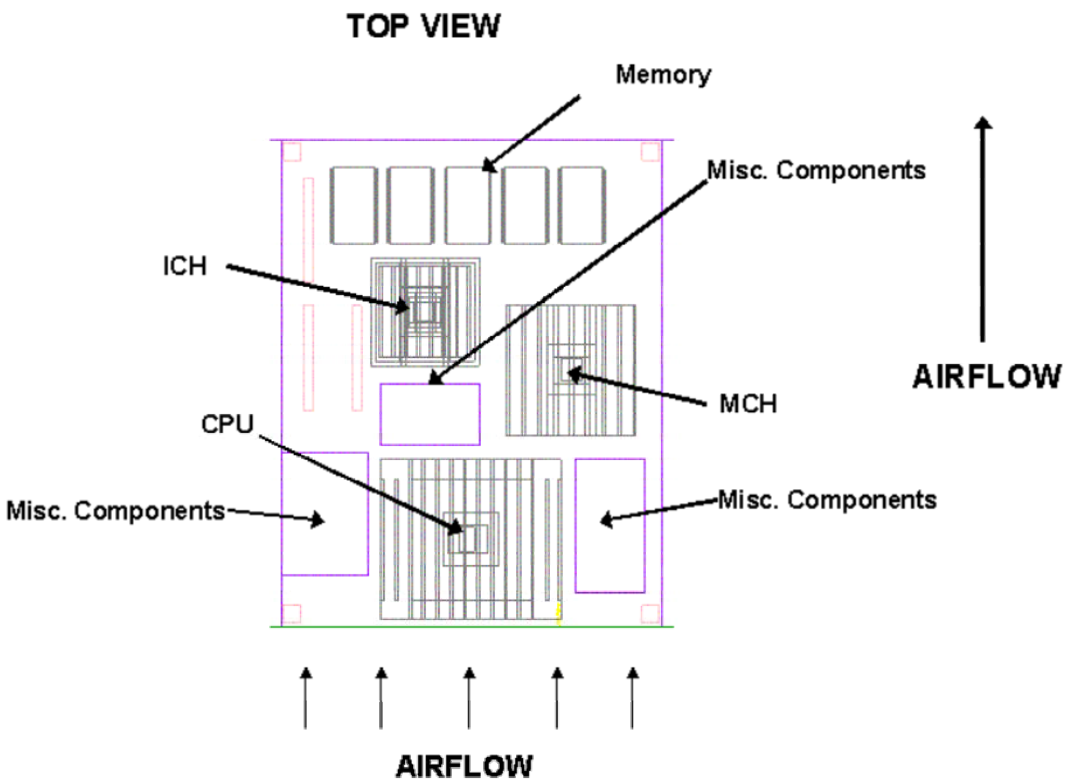
The maximum component temperature for Intel® processors and chipsets is generally specified as T_{Jmax} or $T_{case\ max}$. As shown in Section 2.1.2, T_{Jmax}, T_{LA}, and Thermal Design Power are used to determine what the required thermal resistance for the thermal solution is needed to keep the components within their operating temperatures.

The processors best suited for small form factors include the Intel® Pentium® M, low power Pentium® III, and the low power Celeron® families. These processors are ideal, due to high maximum junction temperature and low Thermal Design Power. With careful component selection and accounting for the system boundary conditions, an optimized thermal solution can be developed for small form factors.

2.2.2. Component Placement

Another factor to consider once the processor and chipset have been selected is the actual placement of the components on the system board. It is important to place the components on the board so that the airflow passing through the processor thermal solution is not preheated or blocked by other components for maximum cooling effectiveness. Figure 3 shows an example of a small form factor board with optimal component placement. This placement is for thermal optimization and does not take into account other design constraints such as routing.

Figure 3. Thermally Optimized Component Placement



As shown in Figure 3, the processor is at the leading edge of the board to prevent preheating and airflow blockage. The next most critical component, the MCH, is then placed on the board so that it can benefit from the airflow that bypasses around the processor thermal solution. The main idea to take away from this example layout, is to account for all components on the board in the system thermal solution design.

2.2.3. Thermal Solution Design

The actual design of the thermal solution should take into account all of the factors mentioned in the preceding sections of this document. The system and thermal solution designer should have a good idea of what type of solution needs to implemented based on system boundary conditions and component specifications.

To develop an optimized thermal solution, whether it is passive, active, or natural convection, designers can take advantage of thermal modeling tools. Performing system level thermal modeling early in the design cycle will allow designers to develop a solution that will solve their thermal challenges.

Thermal modeling can test options when designing a computer system. If modeling results indicate undesirable conditions, parameters can be varied such as increasing airflow, moving the location of system fans, changing the components to lower power dissipating parts, or rearranging the components in the chassis. Analyzing multiple tradeoff scenarios can be achieved with thermal modeling and help optimize the thermal solution to meet component requirements.

With proper system-level thermal modeling, the thermal solution designer can optimize thermal solutions with confidence in their performance, prior to fabricating hardware. This will result in better solutions, lower design time, and faster integration.

3.0 Thermal Solution Types

The three typical types of thermal solutions implemented in small form factor cooling include active, passive and natural convection heatsinks. The previous sections in this document described design considerations and recommendations. The following sections will highlight benefits and examples of each type of thermal solution, particularly for Intel® processors and chipsets.

3.1. Natural Convection Heatsinks

Natural convection thermal solutions are highly desired solutions for small form factors. A natural convection heatsink is designed without a fan and relies only on natural airflow development by thermodynamic effects. The main benefits of natural convection cooling are high reliability and the absence of fan noise. Fans also have moving parts, which eventually break and cause the system to be unavailable.

Emphasis must be placed on optimizing a heatsink for the given conditions, due to the absence of forced airflow in a natural convection system. There are many different market segments that take advantage of natural convection cooling, but there is not one industry wide specification. While this retains flexibility in designing thermal solutions, it makes it difficult to design a standard solution for a given processor that will be applicable for all small form factors. In order to ensure a successful solution, it is critical to perform thermal analysis and modeling as explained in Section 2.2.3.

When performing the thermal modeling, the single most important consideration is the chassis venting for a natural convection solution. Since natural convection relies on naturally generated airflow, the size and placement of the vents in a chassis need to be optimized.

There are limits to using natural convection thermal solutions in small form factors. Most small form factors don't have the space for a large thermal solution, which results in a maximum cooling limit per component. For Intel® processors the cooling limit in small form factors is approximately 10 W. There are a number of Intel® processors that fit within this thermal envelope, as mentioned in Section 2.2.1. The following section shows an example of a natural convection solution for the Ultra Low Voltage Intel® Celeron® processor.

It is important to note that all parameters must be considered in determining the natural convection cooling limit including T_{LA}, T_{Jmax}, form factor constraints, venting and Thermal Design Power.

3.1.1. Ultra Low Voltage Intel® Celeron® Processor

The following example of a natural convection thermal solution was designed in a small form factor that measures 170 x 170 x 50 mm, which represents a typical system chassis for the Mini-ITX* form factor. The guidelines and recommendations presented in this section are based on specific parameters. It is the responsibility of each product design team to verify that thermal solutions are suitable for their specific use.

The following table shows the thermal specifications for the ULV Celeron® processor and the required thermal solution performance at various local ambient temperatures. The thermal resistances are color coded to show the feasibility of achieving a natural convection solution. The higher the T_{LA}, the more challenging it is to develop a natural convection solution that meets the thermal target. This table it shows that for the 400 MHz ULV Celeron® processor, it is very possible to develop a solution up to a T_{LA} of 70

°C. For the 650 MHz ULV Celeron® processor, the table shows that once the T_{LA} is greater than 55 °C, a workable solution is increasingly difficult and once beyond 70 °C it is challenging-to-impossible to develop a suitable natural convection solution.

Table 1: Ultra Low Voltage Intel® Celeron® Required Thermal Solution Performance

Ultra Low Voltage Intel® Celeron® Processor			Required Thermal Solution Performance at Various Local Ambient Temperatures					
			40 °C	45 °C	50 °C	55 °C	60 °C	70 °C
Frequency MHz	TDP Max (W)	T_J Max (°C)	Ψ_{JA} (°C/W)	Ψ_{JA} (°C/W)	Ψ_{JA} (°C/W)	Ψ_{JA} (°C/W)	Ψ_{JA} (°C/W)	Ψ_{JA} (°C/W)
400	4.2	100	14.2	13.0	11.9	10.7	9.5	7.1
650	8.3	100	7.2	6.6	6.0	5.4	4.8	3.6

Notes:

- Specifications (TDP, T_J) are provided for reference only. Refer to the latest datasheet for the most recent data.
- Ψ_{JA} = (T Junction – T Ambient)/ TDP, junction-to-ambient thermal resistance for the thermal solution.
- The feasibility was determined by thermal modeling.

FEASIBLE **CHALLENGING**

Notice that it is easier to design a natural convection thermal solution as the local ambient temperature and the power decrease.

An example solution has been designed for the 650 MHz Ultra Low Voltage Intel® Celeron® processor at a T_{LA} of 45 °C using thermal modeling software. The following is a list of the system parameters and thermal solution characteristics used in the simulation.

- T_{LA} = 45 °C
- TDP = 8.3 W
- Chassis dimensions: 170 mm X 170 mm X 50 mm
  – Note: the ends of chassis have venting with 100 percent free area ratio
- Heat sink dimensions: 63 mm X 52 mm X 28 mm
  – Base thickness: 4 mm
  – Fin height: 24 mm
  – Fin thickness: 1.15 mm
  – Fin Spacing: 3.2 mm
  – Number of fins: 15
  – Material: Extruded Aluminum

Thermal modeling of the above parameters indicate that the junction-to-ambient thermal resistance for this solution is 6.5 °C/W in natural convection. With this performance the heatsink could sufficiently cool the 650 MHz ULV Celeron® processor in a system with a T_{LA} up to 45 °C.

This is one example of a natural convection solution for small a form factor. Depending on system and chassis configuration, a different thermal solution can be optimized for the intended system. Parameters could be changed to obtain a smaller solution such as using a lower power processor or lowering the maximum local ambient temperature.

3.2. Passive Thermal Solutions

Embedded computer systems and small form factors use a number of different types to thermal solutions to keep the processor and chipset within their operating temperatures. The most common method is the use of passive heatsinks with system airflow. The majority of these passive solutions are used on processors and chipsets which are placed in a chassis with a rack configuration. The racks accommodate a number of computer boards that generally have a small spacing between boards. The spacing limits the available height for a thermal solution and restricts the use of an active thermal solution. Instead, the chassis have fans that supply the airflow to the system. There are usually a number of redundant fans in the rack. Should one break, then the additional fans provide airflow until the broken fan can be replaced.

Since the majority of embedded market customers use passive cooling solutions, Intel's Embedded Architecture Division actively develops reference thermal solutions for processors and chipsets suitable for use in small form factors. Intel® processors such as the Pentium® M, LV Pentium® III, LV Celeron® and ULV Celeron® families have a number of reference designs described in their respective processor thermal design guides. These solutions can apply toward a number of small form factors that use passive cooling with system airflow. Refer to the design guides on the Embedded Intel® Architecture developer site, http://developer.intel.com/design/intarch/. In addition to reference designs, the thermal design guides contain design considerations and thermal testing metrology.

3.3. Active Thermal Solutions

Active thermal solutions are heatsinks that include an integrated fan. In general, small form factor boards do not use active thermal solutions primarily because of fan reliability, size of the fansink.

For systems that can integrate fansinks there are a number of options available. Fansinks are usually used on processors with higher power than typical low voltage processors. Typical fansinks for these processors are approximately 23-45 mm tall. Current solutions available have relatively small footprints of 50 mm X 50 mm. These fansinks can cool a 24.5 W Pentium® M and a 30 W Pentium® 4-M processor in a system with a T_{LA} of 45-60 °C. These solutions can also be used for any mobile type processor in the Micro-FCPGA and Micro-FCBGA packages. For more information on these solutions refer to applicable Processor Thermal Design Guide.

As with any system, the overall system thermal solution must be considered in the design. There are other components such as the northbridge, southbridge, and memory that may require either a thermal solution or some amount of airflow. The airflow provided to these other chips can come from the air leaving the active fansink or by placing fans in the system to provide air movement in and out of the chassis. It is very important to perform thermal simulations and testing on the chassis to optimize the airflow and venting in the system to provide maximum cooling effectiveness.

4.0 Conclusion

The design of thermal solutions for small form factor computing systems has to take many different parameters into consideration, including:

- board size
- available height for thermal solution
- maximum local ambient temperature
- airflow

In addition to the system conditions, the processor and chipset specifications and location of these components must be considered. After the system has been defined, there are three basic types of thermal solutions: natural convection, active, and passive. Each of these have benefits and limitations that designers can use to their advantage. With proper thermal design considerations, Intel® processors and chipsets can provide high performance processing power in small form factors.