Kinetic Heat Sink

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Abstract

Conventional heat sinks for processors achieve improved heat transfer efficiency by impinging ambient air over stationary fins. Further improvement in the air film heat transfer coefficient through increased air speed becomes asymptotic and invariably results in undesirable acoustic noise. The Kinetic Heat Sink (KHS) is a novel concept that utilizes rotating metals fins to transfer heat to the ambient air. The configuration allows high-speed relative motion between surrounding air and fins with the potential of a high heat transfer coefficient at practical flow rates and rotational speeds. Improved efficiency of heat transfer is anticipated because of higher relative tangential velocities offered by the rotating fins and moving air compared to a conventional heat sink configuration. The need to move the fins relative to the stationary heat source, however, imposes a technical challenge. A highly conductive thin liquid film to couple the stationary heat source to the moving fins is required to demonstrate the merit of the KHS. The concept of the KHS has been evaluated in a number of prototypes that have been built and tested. The lessons learnt through a series of prototype KHS designs are summarized. The technical and performance challenges encountered during the feasibility testing of a KHS are then outlined.

Key words: heat sink, heat source, moving fin, fluid film, relative velocity, thermal resistance

Background

Thermally efficient cooling technology is mandatory to manage the power dissipated by a computer processor. Air-based cooling methods are generally preferred because of their simplicity and cost effectiveness, but have been recognized as a challenge in supporting a high power processor. Most cost-effective cooling systems use either a separate fan and a metallic heat sink or a combined fan-heat sink assembly. A fan with a heat sink assembly suffers from two types of inefficiencies. First the air flow, generated by the fan and primarily intended to remove heat convectively from the fins, leaks to other regions not participating in the cooling effect. Second, the formation of a boundary layer over the fins produces a non-conducting air film which increases the thermal resistance.

As the processor power continues to increase due to high leakage current and device density, the combined mass/volume of the fan-heat sink system needs to grow in order to keep up with the desired improvement in thermal resistance. To meet future requirements alternative approaches must be considered. As processor power dissipation increases, innovative cooling methodology is likely to become a determining factor in the success of a product.

Concept of a Kinetic Heat Sink

A Kinetic Heat Sink (KHS) integrates the function of a fan and a passive (i.e., stationary) heat sink into a single rotating metallic fan blade. Figure 1 shows the configuration of a Kinetic Heat Sink schematically. The general concept is discussed in greater detail in Ref. [1].

The heat dissipated by a microprocessor is transferred to a modified lid, similar to any other electronic package, through a first level thermal interface material (TIM). However, in the next stage of heat transfer, the heat flux is directed to the rotating shaft through a thin liquid

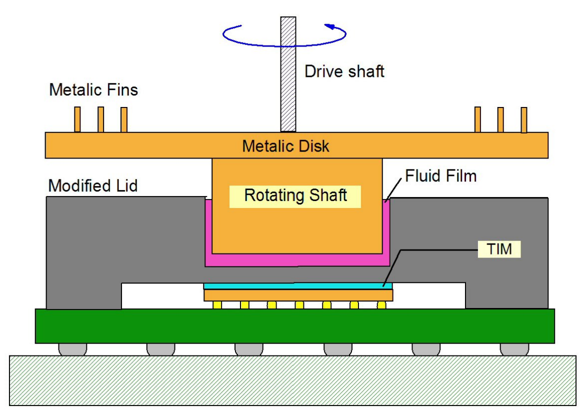


Figure 1. Schematic of a Kinetic Heat Sink.

film with desirable fluid dynamic and heat transfer properties. The fluid film is essentially a second level TIM. The shaft, in turn, supports a metallic disk “optimized” for heat transfer with the ambient air. The metallic fins of the rotating disk are exposed to ambient air with higher relative velocity, thus promising an efficient heat transfer mechanism.

Figure 2 shows the limits of air cooling with different heat transfer configurations [2]. To obtain thermal resistance of less than 0.5 K/W (degree Kelvin per Watt), new design concepts are needed. The KHS is a research attempt to achieve a lower thermal resistance without requiring high velocity air flow over stationary fins.

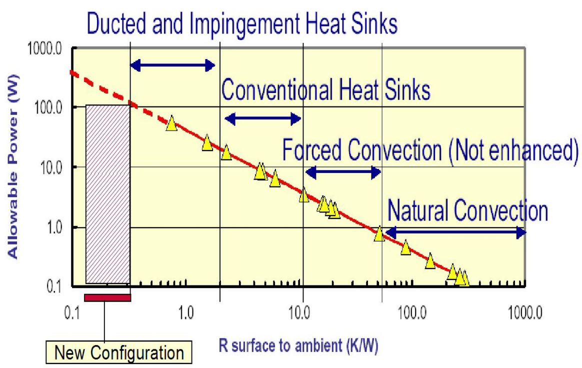


Figure 2. Air Cooling Limits [Ref. 2]

Using a thin film of fluid (order of um in thickness) between a stationary and moving member, a minimum heat resistance configuration can be realized. Use of conducting nanoparticles embedded in the fluid can potentially facilitate efficient heat transfer between the stationary and moving parts of the KHS. One of the key challenges in a KHS is the sealing technology required to contain the fluid film during the lifetime of the cooling system.

A KHS configuration offers many positive attributes. A multitude of heat sink integration problems can be elegantly resolved, as will be discussed in later sections.

Feasibility of the KHS Concept

To establish the merit of the KHS, a spindle motor from a 2.5” disk drive was canni-balized and configured as shown in Figure 3. The motor drive has a fluid dynamic bearing at its center with a “moving shaft” design. A blade structure made of a thin (0.8 mm) aluminum plate (diameter 48 mm) was constructed and attached to the hub of the motor. Two 5 ohm resistors were used in series as the heat source. To avoid any ambiguity in the cooling mechanism, a flat non-conducting plate was used as a shroud so that any air flow due to blade rotation would not directly cool the resistors or the aluminum heater block. The intent of this experiment was to differentiate the effect of a stationary fin and a moving fin on the cooling capability of a KHS configuration.

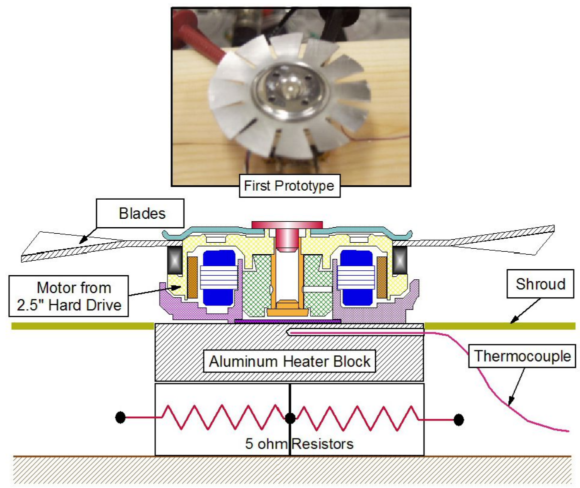


Figure 3. First Prototype of a KHS.

Figure 4 summarizes the effect of spinning blades vs. a stationary blade. Also shown is the effect of natural convection over the heater block prior to attaching the motor assembly on the aluminum heater block. It can be seen that turning the motor on does produce a reduction in source temperature from 145°C to 85°C at 8 W power dissipation. The effective thermal resistance drops when the motor is turned on.

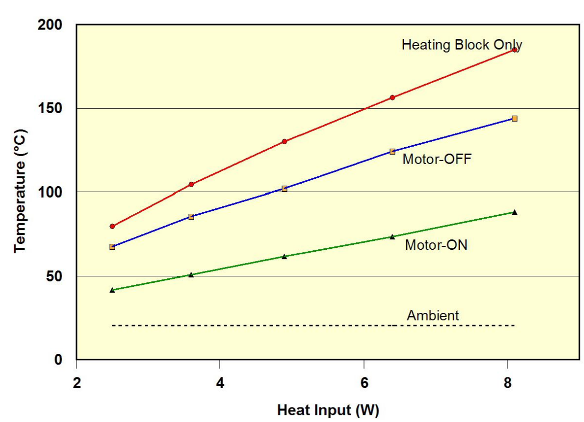
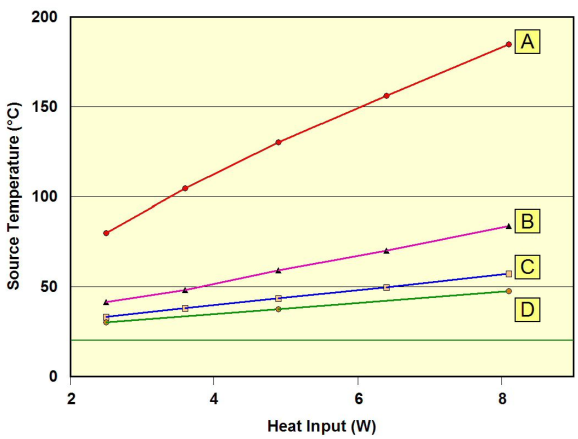


Figure 4. Feasibility Test Data of a KHS.

First Generation Prototypes

With the encouraging results of the feasibility test described above, several new prototypes were built to compare the effectiveness of various blade designs. Figure 5 shows two new blades made from a thicker (6.5 mm) aluminum block with 45 mm diameters. These prototypes constitute the 1st generation design.

In comparison to the two cases A & B described already, the two new cases C and D have a blade density increased from 13 (case-C) to 24 (case-D). The thermal resistances are correspondingly reduced from 7.6 °C/W for case-B to 4.3 °C/W for case-C and 3.1 °C/W for case-D. The improvement found in these new designs led to a series of blade geometries for a KHS which are effectively described in Ref. 3.



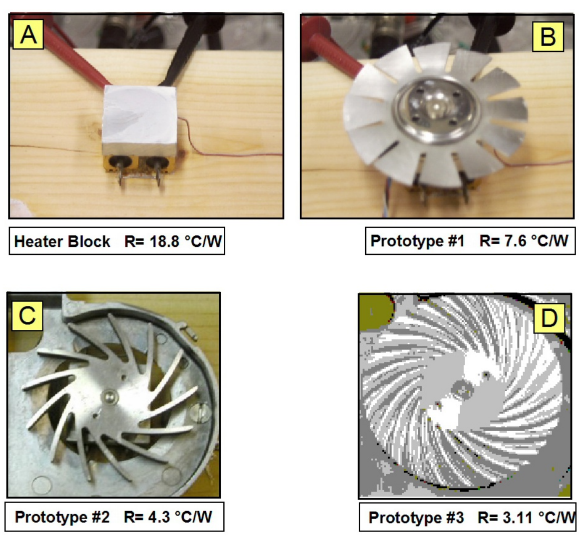


Figure 5. Improving KHS with New Blades.

While the trend in thermal resistance improvement was in the right direction, the absolute resistance values were not competitive enough. The target was to achieve an effective resistance of the order of 0.5 °C/W. Two areas of the KHS concept required more focused evaluation. Figure 6 shows the components of thermal resistance. Two problems areas: 1) the thermal resistance of the fluid interface and 2) fin-to-air film heat transfer coefficient appear to impact the effective thermal resistance of the KHS prototype. Progress in reducing the thermal resistance can be achieved only by creatively attacking these two problem areas.

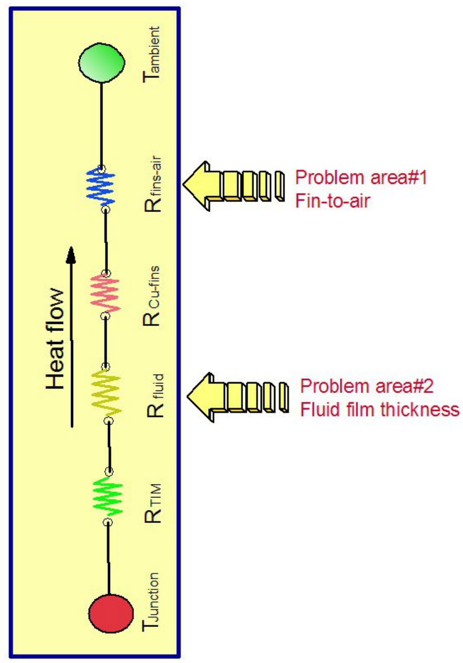


Figure 6: Components of Resistance.

The two sources of thermal resistance are complex to capture through fluid dynamic modeling. Initially, a simplified approach to detect the major source of the thermal resistance was undertaken. The physical parameters of the prototype (case-C) were used to construct an FEM model with the corresponding thermal conductivity (k) values defined in Figure 7. The air-to-fin film heat transfer coefficient was changed from 50 to 250 W/m^2-K until the source temperature matched the measured value of 120°C at 30W power dissipation. Figure 7 shows that the largest temperature gradient occurs across the oil film with k = 0.3 W/m^2-K). In reality the oil film is not static and is likely to circulate radially due to centrifugal forces generated by the rotational motion of the shaft. Thus the heat energy is not only transferred conductively, but also transported convectively.

Challenges Associated with the Fluid Film

A simple oil film was used to construct the experimental prototypes even though its conductivity is not as high as that of a TIM material. The viscosity of the fluid film ought to be low in order to minimize rotational power while higher thermal conductivity is an important requirement for this application. Research in the area of nanoparticles may yield better kinds of film for the KHS in which both viscosity and heat transfer capabilities are simultaneously met.

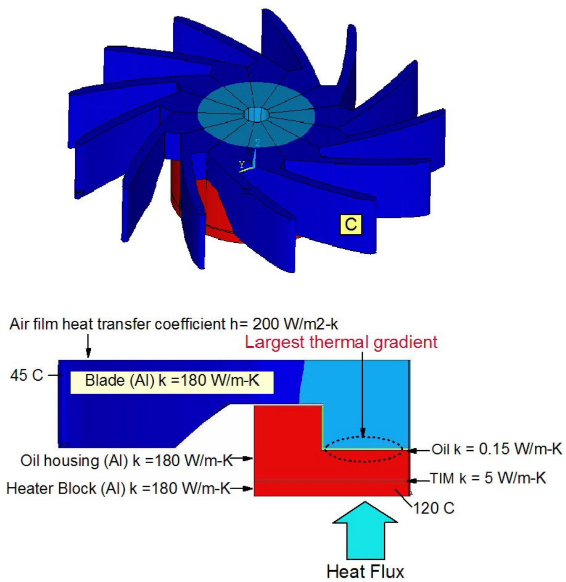


Figure 7. Thermal Model of Case-C KHS.

Potential of liquid metal was evaluated for the KHS application. Liquid metal has high thermal conductivity. However, the liquid metal surface that is exposed to ambient air reacts aggressively with oxygen, forming a solid-like compound within minutes of operation. This makes it unsuitable for a KHS application without the use of sophisticated hermetic sealing.

Since heat from the source can also be convectively transferred, a fluid with moderate conductivity and thermal capacity could be a good candidate. The presence of fluid film in the rotating structure provides several opportunities in constructing new innovative cooling solutions. Modification of the rotating shaft surface with appropriate geometric structures, for example, can produce a pumping action which can be used to transport heated fluid from the vicinity of a heat source to the surface exposed to ambient air. A set of related configurations are discussed in Ref. 4.

Since the fluid film problem requires new materials as well as complicated construction of pumping structures in order to reduce the thermal resistance, new prototypes were built with a larger fluid film surface. This larger surface reduced the effective thermal resistance due to the oil film and allowed the second key component (fin-to-air resistance) to be studied for resistance minimization.

Second Generation Prototype

The first generation prototypes were difficult to fabricate because of their geometric scale. They constrained the air flow generation and fin-to-air heat transfer mechanisms. Such limitations encountered in the 1st generation prototypes were rectified in a 2nd generation prototype. The new prototype was built to study the key parameters contributing to the thermal resistance of the KHS. Factors considered to be important are:

- air flow velocity
- motor rotating speed
- boundary layer thickness
- fin geometry
- fin density

Figure 8 shows a schematic of the 2nd generation prototype. It was designed to control the air flow rate and disk rotation speed independently. The fins on the rotating disk were constructed to have an arc-like geometry so that the effect of boundary layer on fin-air heat transfer could be determined. A baffle plate as shown in Fig. 8 facilitated the stripping of the boundary layer.

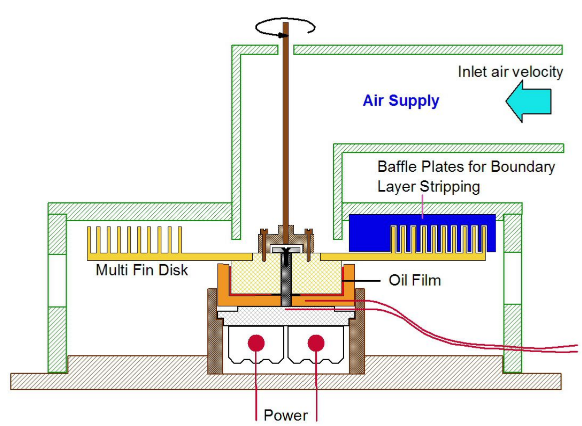


Figure 8. Schematic of 2nd Gen. Prototype.

Figure 9a shows a fabricated KHS with a disk having a single row of fins. Its diameter is greatly increased compared to the 1st generation prototypes so that conventional machine tools could be used in its fabrication. The outer diameter of the rotating disk is (90 mm), and the disk is designed to be interchangeable with another disk with a different fin density. Figure 9b shows a multi-fin construction.

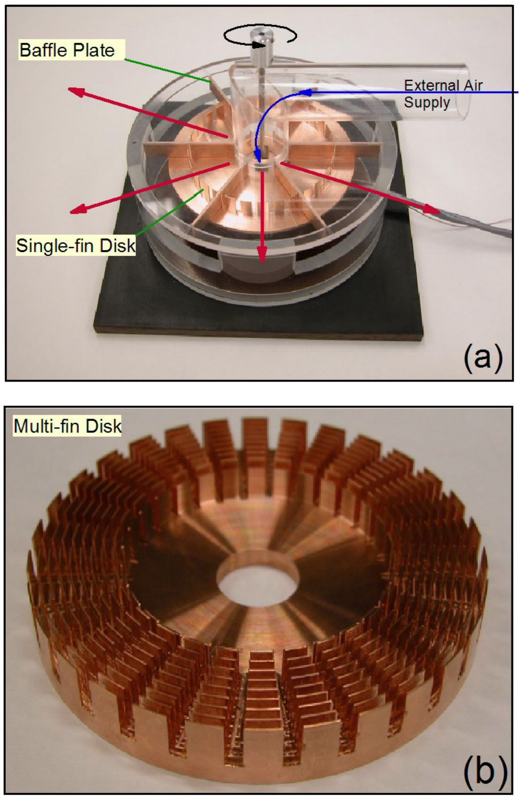


Figure 9. Design of 2nd Gen KHS.

Ultimately a modular KHS with a multi-fin disk and an integrated drive motor is envisaged for industrial applications as shown in Fig. 10.

Extensive tests were conducted and the data analyzed on the 2nd generation prototype. Figure 11 illustrates an important characteristic of the KHS. Here the heat source temperature is plotted as a function of rotational speed for three different air flow velocities (3.5 m/s, 7.0 m/s and 14.0 m/s) as measured at the inlet port (2.5 cm diameter). For the 3.5 m/s inlet air velocity, the source temperature drops by 10°C as the motor speed is increased from 0 to 2500 rpm. This is the unique feature anticipated from a KHS. Beyond 2500 rpm, an increase in motor speed does not produce a measurable drop in source temperature.

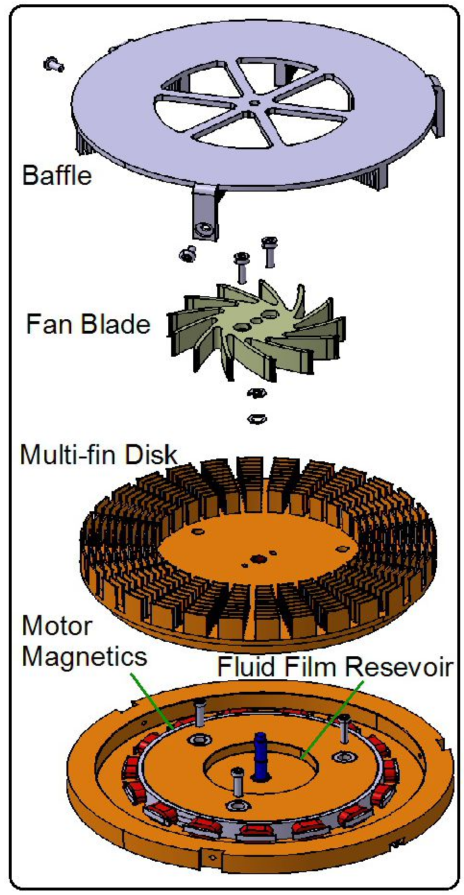


Figure 10. An Integrated KHS.

The most surprising observation is that at the 7 and 14 m/s inlet air velocities the motor rotational speed has minimal effect on the source temperature. Thus there is an operating region where the rotational speed does contribute to improved thermal resistance. However, when the *supply air velocity* is increased to a higher level, the corresponding advantage of the KHS becomes less significant.

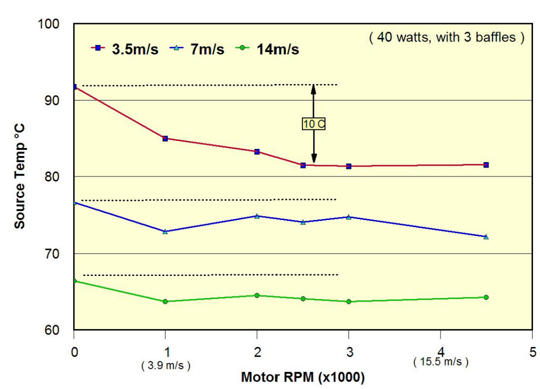


Figure 11. Performance at Selected RPM and Air-flow Velocity.

In order to develop a better understanding of the factors impacting air-to-fin heat transfer, a Fluent^{TM} based FEM model was built. The results of the study can be published elsewhere based on the interest of the development community.

Positive Attributes of a KHS

Once the potential to reduce the thermal resistance is asserted, additional design advantages can be considered. Of specific interest is the leveraging of the fluid film to manage assembly tolerance and stress at the TIM-1 interface.

Figure 12 shows a schematic view of a modified KHS where the TIM-1 interface is designed to have compliance in the Z direction (axis of the rotating shaft). Thus the height variation encountered in conventional packages, as well as in 3D packages, can be easily negotiated with a simple mounting arrangement. Also, by means of spacers, preferably a three-point gap element, the high stress usually exerted by a heat sink on the die can be reduced. In the best mode realization the TIM-1 interface itself can be made compliant enough to conform to the surface of the die thereby minimizing the thermal resistance while avoiding the TIM paste voiding problem.

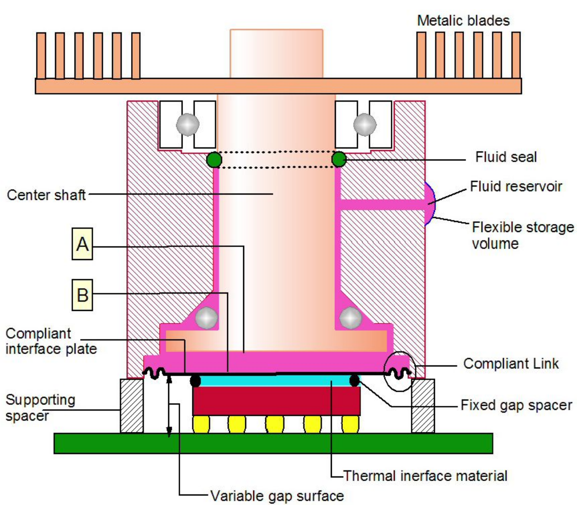


Figure 12. Positive Attributes of a KHS.

It is noted that the KHS in this example transfers heat through an oil film first and eventually transfers it to ambient air. In specialized applications the medium can be a liquid different from air. Such an embodiment is described in Ref. 5, where a KHS plays the role of an efficient heat spreader.

Summary

The concept of a Kinetic Heat Sink (KHS) has been presented and early feasibility of the concept has been demonstrated. Two generations of prototypes have been developed and tested to identify key parameters contributing to the thermal resistance of a KHS. The fluid film provides a substantial design challenge. Experimental evidence shows that a KHS is most sensitive to rotational speed when the air flow rate is low. Furthermore, new advantages can ensue from a functional KHS in which the fluid film is leveraged. Further effort is needed to realize and quantify the full potential of a KHS

Acknowledgment

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