

# Thermal Design Simulation Software “HIEROH”

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## ABSTRACT

Heatsinks are frequently designed specifically for the equipment to which they are to be applied. In addition to a trend toward shorter development periods for equipment that incorporates heatsinks, it has become more common to consider cooling capacity from the earliest stage of overall equipment design. This has led to a need for faster thermal design.

In the past reliance has been placed on very simple manual calculations or computational fluid dynamics (CFD) programs such as the finite volume method, but all of these present problems in terms of low accuracy, difficulty of use and length of calculation time.

As part of our “total thermal solution” extending from the design to the product, Furukawa-Sky has developed the HIEROH thermal design software that is quicker to use.

We also propose spread efficiency as a design guideline for optimization.

## 1. INTRODUCTION

The use of cooling systems ordinarily involves the heat being ultimately dissipated to the air, and in such cases heatsinks play an important role. Heatsinks are frequently designed specifically for the equipment to which they are to be applied, and designing them requires a balanced optimization of thermal performance, size, weight, and so on.

### 1.1 Conventional Thermal Design

In conventional thermal design two methods of thermal analysis have been used:

a) 1-dimensional analog analysis

Based on a certain set of assumptions, 1-dimension calculations (fin calculations <sup>1)</sup> and so on) are carried out, achieving an approximate understanding of performance.

For example, if we solve an equation for thermal balance under conditions in which the end is adiabatic, we obtain

$$T = C_1 \exp(kx) + C_2 \exp(-kx)$$

Since analog solutions do not depend on the fineness of the mesh, they have the advantage of providing infinite fineness, but the information that can be obtained is only 1-dimensional; it cannot yield 2-dimensional information like heat diffusion in the base plate.

b) 3-dimensional digital solution

For 3-dimensional analysis of the heatsink as a whole, reliance has been placed on programs for the finite-element method or the finite volume method <sup>2)~4)</sup> but the procedure is complex (pre-processor, solver, post-processor), and the setting of conditions —headed by mesh

generation— requires a certain level of skill.

Also the computer must have a great deal of memory and calculation times are long, typically several hours for large-scale jobs.

Some problems associated with conventional design methods are as follows:

- 2-dimensional information could not be obtained (in the case of fin calculation);
- In the digital solution, calculations could be performed for any desired configuration but the calculations required skill and were normally performed by a specific operator.
- Only the expected temperature was displayed; there was no display of design guideline to improve performance.
- For weight, etc. calculations were done separately from the simulation software, resulting in inconvenience.

### 1.2 Effectiveness of Quickly Usable Software

With the quicker pace of development for equipment incorporating heatsinks, it has become desirable to speed up thermal design as well.

In the past it was sufficient to deal with the heatsink at the later stages of design, but recent increases in heating values have created a need for thermal design to be taken up from the earliest stages of development. In such cases it is no longer effective to devote a lengthy period simply to carefully estimating thermal performance using a specific model; it is now necessary to arrive at an estimate very quickly —in a few minutes. It is also desirable that estimating thermal performance be easily accomplished, even by persons without expertise in thermal analysis.

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We have therefore developed software that can be mastered quickly by anyone. And to facilitate arriving at a comprehensive decision, we made provision that information other than thermal performance —such as pressure loss, weight and the like— can be obtained with the same software, and that it would also be possible to display spread efficiency as a design guideline.

## 2. GUIDELINES, MODELING AND PRINCIPLES OF CALCULATION

### 2.1 Guidelines

- Insofar as possible to use analog solutions;
- To apply digital solution only where unavoidable; and
- To enable the obtaining of 3-dimensional information by means of ingenious modeling.

### 2.2 Modeling

We created a model based on a grasp of characteristics (here we set forth the case of a square configuration):

Setting forth the sequence of thermal flow we have:

- 1) Heat spreads over the base plate surface;
- 2) Heat spreads in the fins; and
- 3) Heat is dissipated from the fins to the air.

For purposes of simplification, (reversing the sequence):

- We calculated the fin-to-air dissipation of heat in 3) using the theoretical formula for heat transfer;
- We then calculated the spread of heat in the fins 2) in terms of fin efficiency (Figure 1).

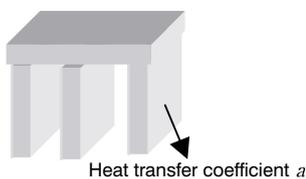


Figure 1 Heat transfer coefficient of heatsink.

Assuming that the fins have been placed with sufficient density with respect to the base plate surface, and that the hypothetical heat transfer coefficient of the base plate surface is  $a'$ ,  $a'$  may then be calculated as a (heat transfer coefficient of the fins)  $\times$  (the surface multiple seen from the base plate surface)  $\times$  (fin efficiency) (Figure 2).

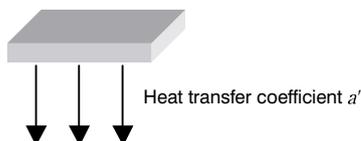


Figure 2 Hypothetical heat transfer coefficient of base plate.

Again the base plate surface is converted to a circle having the same area as the base plate surface (Figure 3).

### 2.3 Principles of Calculation

First let us explain on the basis of a 2-dimensional calculation.

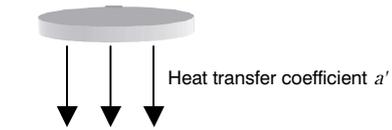


Figure 3 Base plate converted to circle.

#### 2.3.1 Calculations for Inside of Exothermic Device

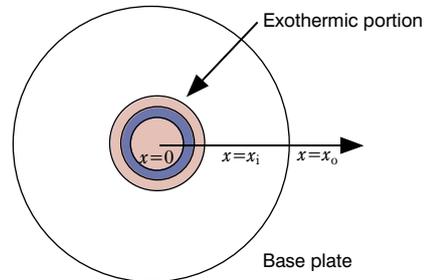


Figure 4 Calculation model for inside of exothermic device.

If we apply the equation focusing our attention on the minute part forming the innermost concentric circle shown in Figure 4, and if we let  $x$  be the distance from the center,  $\lambda$  the thermal conductivity,  $d$  the thickness, and  $q_0$  the exothermic heat per unit volume, we find that temperature  $\theta$  satisfies

$$\begin{aligned} d \times [ \{-\lambda(2\pi x)d\theta/dx\}_x - \{-\lambda(2\pi x)d\theta/dx\}_{x+dx} ] \\ = -a'(2\pi x)\theta dx \text{ (heat transfer term)} \\ + \pi \{ (x+dx)^2 - x^2 \} dq_0 \text{ (exothermic term)} \end{aligned}$$

Since the first term on the right side is dramatically smaller than the second term, it may be omitted giving

$$\lambda \frac{d}{dx} \left( -x \frac{d\theta}{dx} \right) = xq_0$$

Here if we take  $q_0 / \lambda = 4k$  we may write

$$-x d\theta/dx = 2kx^2 + c'$$

and since, when  $x = 0$ , the slope of temperature becomes 0, we get  $c' = 0$ . And thus we find that  $\theta = -kx_2 + c$

At the boundary, analytical continuation is applied between this thermal field and the one described by the equations in Section 2.3.2 so that agreement is achieved in the value and gradient, and the two fields may be represented by  $C_1$  and  $C_2$ .

#### 2.3.2 Calculations for Outside of Exothermic Device

In Figure 5, if we construct a differential equation considering the thermal balance between  $x$  and  $x+dx$  in the  $x$  direction, we obtain

$$d \times [ \{-\lambda(2\pi x)d\theta/dx\}_x - \{-\lambda(2\pi x)d\theta/dx\}_{x+dx} ] = a'(2\pi x)\theta dx$$

which may be ordered as

$$\frac{d}{dx} \left( x \frac{d\theta}{dx} \right) = \frac{a'}{\lambda d} x\theta$$

and if we substitute  $m = \sqrt{\frac{a'}{\lambda d}}$  using a progression solution with  $\theta = \sum A_n \left( \frac{1}{2} mx \right)^n$

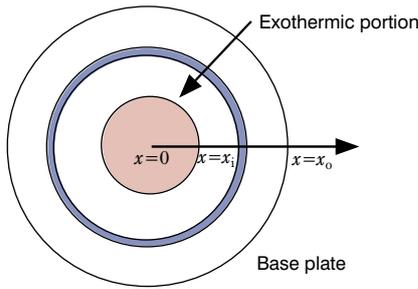


Figure 5 Calculation model for outside of exothermic device.

we can find

$$A_n = \frac{1}{2(n!)} \times A_o$$

If we take  $A_o = 1$ , it agrees with type 1 modified Bessel function  $I(x)$ . Similarly, finding another solution, if we take an arbitrary constant  $\gamma$ , it agrees with type 2 modified Bessel function  $K(x)$ .

Thus it can be seen that  $\theta = C_1 \text{ Bessel } I(mx) + C_2 \text{ Bessel } K(mx)$ .

The conditions for finding  $C_1$  and  $C_2$  are:

the adiabatic end condition  $d\theta/dx=0$  at  $x=x_o$  and

energy balance  $\int_0^{x_o} 2\pi a' x \theta dx = \text{exothermic heat}$

and given that the number of variables is 2 and the number of equations is 2, we can determine  $C_1$  and  $C_2$ .

Solutions can be obtained for the Bessel functions using Allen's approximation equation <sup>5)</sup> and for integral calculus using Simpson's formula <sup>5)</sup>.

### 2.3.3 Pseudo 3-dimensional Calculations

By positing a hypothetical component directly beneath the exothermic device (Figure 6) and calculating the flow of heat into and out of that body, we determined the temperature difference in the thickness direction.

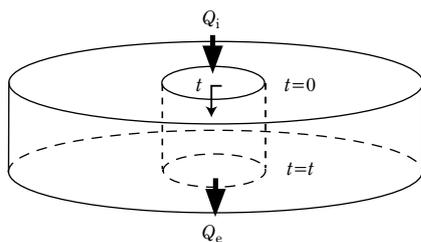


Figure 6 Calculation model for temperature difference in thickness direction (through base plate).

If we construct an equation under conditions of constant heat transfer coefficient, we would hypothetically dispose here a cylindrical component directly beneath the exothermic device, as shown in Figure 6. Taking the variable for the thickness direction as  $t$ , an input heat  $Q_i$  equivalent to the exothermic heat enters this component from above, and the exiting heat  $Q_e$  can be found by the calculations shown in Sections 2.3.1 and 2.3.2 above.

From the lateral direction heat is lost, but, using the hypothetical heat transfer coefficient  $a''$ , if we let

$m = \sqrt{\frac{a''C}{\lambda d}}$  (where  $C$  is the circumference and  $S$  is the cross-sectional area), we may write the solution as

$$\theta(t) = C_3 \exp(mt) + C_4 \exp(-mt)$$

Here the way we treat  $m$  (and by extension  $a''$ ) presents a problem, but nominally we shall treat it as a variable. (It is, however, the case that  $m$  is assumed to have a fixed value irrespective of its position.)

There are three boundary conditions:

$$-\lambda d\theta/dt_{(t=0)} \times S = Q_i \quad (1)$$

$$-\lambda d\theta/dt_{(t=t)} \times S = Q_e \quad (2)$$

$$\theta(t) = \theta_i \text{ (known)} \quad (3)$$

so they may in principle be solved for the three variables.

In (1) if we take  $\beta = 1/\{S(-\lambda)m\}$ ,  $C_4 = C_3 - \beta Q_i$

If we substitute

$$C_3 = [\{Q_i - Q_e \exp(-mt)\} / \{\exp(mt) - \exp(-mt)\}] \times \beta$$

from (2) into (3),

we obtain

$$\beta [\{\exp(mt) + \exp(-mt)\} / \{\exp(mt) - \exp(-mt)\}] Q_i$$

$$- 2Q_e / \{\exp(mt) - \exp(-mt)\} = \theta_i$$

Provided  $mt$  is sufficiently large, the left term will show the behavior of  $\beta$ , i.e.,  $1/m$  (which will be a graph in the form of  $y=1/x$ ), so that with respect to the Newton-Raphson Law it will constitute a "function of good quality" and will be easily solved.

Here, by treating  $m$  as a function without forcibly inserting an inferred value, we can obtain a solution that is self-consistent (not self-contradictory).

With respect to accuracy, we compared similar calculations for thermal conductivity with the finite-element method. (Since modeling for HIEROH was carried out with reference to a practicable heatsink, it does not bear reference to non-practicable heatsinks, such as one having only a single fin.)

Comparing for a number of practicable heatsink configurations using values of the finite-element method as a basis, error fell within a range of -2% to +8%.

### 2.4 Extension to More Complex Configurations

In cases in which the exothermic device is not in the center, it may be approximated by means of circles having different radii, and calculations relating to up-wind and down-wind temperature differences can be done using thermal conductivity and heat transfer coefficient.

And if there is more than one exothermic device, the calculations are carried out on the principle of superposition <sup>6)</sup>.

### 2.5 Comparison of the Amount of Calculations

Conventionally, taking that the heatsink as a whole consists of several million joints of mesh, and that there are seven variables —air flow in three directions, pressure, temperature, turbulence energy, turbulence decay rate, etc., tens of millions of equations were solved, requiring several hours of calculation time.

Modeling in the way described means that these could

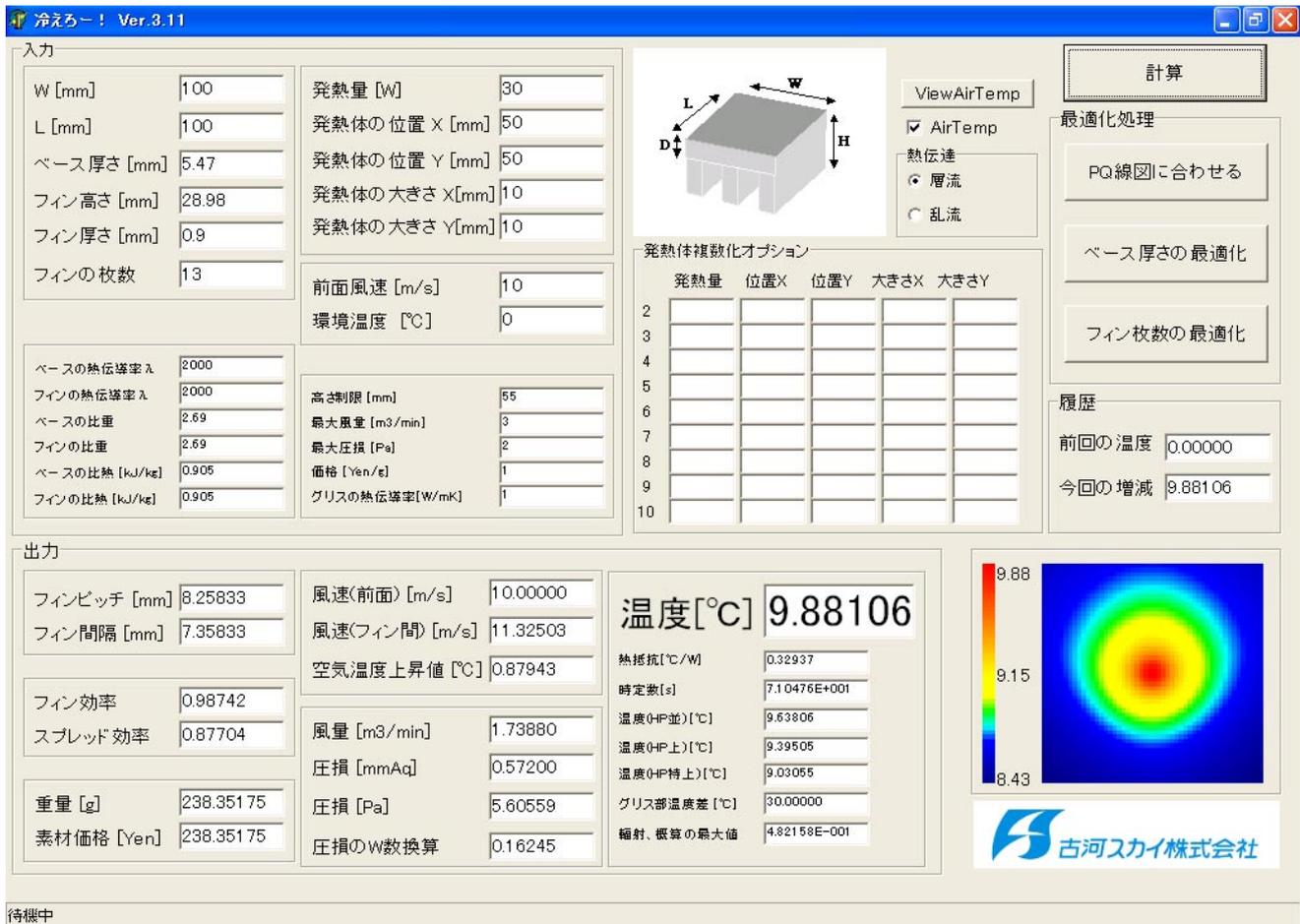


Figure 7 Man-machine interface of HIEROH software.

be summarized by a few hundred equations, and operation was greatly speeded up.

### 3. REPRESENTATIONAL PROGRAMMING

When we were successful in establishing the calculation method described in Section 2, we set about programming in an easy-to-use representational form that will run on a Windows† platform.

#### 3.1 Screen and Features of How It Is Used

- Everything is displayed on a single screen making it easy to see, and reducing setting mistakes during data entry.
- Operation does not require awareness of pre-processor, solver, or post-processor or mesh generation, so that there is no need to carry out operations that were conventionally unnecessary in deriving estimated values from conditions.
- How it is used  
On a PC running Windows, double-click on the HIEROH logo and simply enter numerical values for size, exothermic heat, etc. into the table. Then click on the CALCULATE button at the top right and the calculated results, including a contour drawing,

will be displayed. There is also a function, to be described below, that will optimize the configuration. Simply click on the CALCULATE button for optimizing to be performed automatically.

#### 3.2 Features of Operation

- Easy on/off switching; just double-click on the logo and the final results from the previous time loads automatically. When terminating, the calculation that was last performed is saved automatically. It has the operational feel of opening and closing a notebook.
- Quick display: calculations are completed in less than 1 second, even on older computers with CPU clock speeds in the 500-MHz order (Furukawa-Sky test values). Since a single set of calculations can be done so quickly, the automated calculations to be described below can also be completed quickly.
- Includes information on weight, pressure loss, etc. in the display, so there is no need to perform separate calculations.
- Displays a contour diagram, allowing checking of data entry.
- Rise in air temperature can be calculated: In cases in which air speed is slow, even an increase in fin area has only a limited effect in reducing thermal resistance.

† Windows is a registered trademark of Microsoft Corp.

- Displays time constant: The time required for a rise in temperature to approximately 63 % of steady state is displayed.
- Displays temperature difference at the thermal compound part: Temperature difference resulting from typical contact resistance is displayed.
- Displays wattage for power loss: Power loss is normally displayed in a unit of pressure such as Pa, but to be consistent with fin power, etc., there is also a display converted into Watts.
- Maximum radiation: When the radiative coefficient has been increased, the estimated value for the maximum wattage that can be dissipated by radiation is displayed.
- Comparison with previous time: There is a function that retains the value calculated the previous time and displays the difference from it. When conditions have been modified, this makes it easy to see what kind of change has occurred.
- Physical properties can be set independently for the fins and base plate, so that it is equally applicable to crimped fins.

### 3.3 Automation

- Fitting to the PQ curve diagram  
If a PQ curve diagram for the fins is given, the working point can be found as shown in Figure 8.

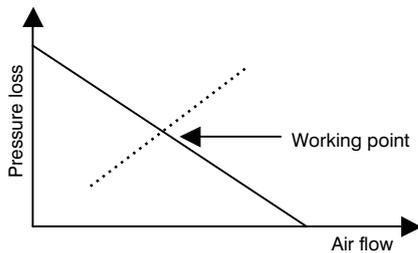


Figure 8 Relationship between pressure loss and air flow rate.

- Optimizing the number of fins  
With the fins kept at constant conditions, the number of fins is changed (Figure 9). As the number of fins increases, the surface area increases but the air flow tends to decrease and the point of minimum thermal resistance can be found.

By suppressing the amount of calculation it becomes possible to increase speed. The process of optimization, which conventionally took half a day or even a whole day, can be done in about 30 seconds (Furukawa-Sky test values).

## 4. SPREAD EFFICIENCY AND OPTIMIZATION

### 4.1 Spread Efficiency

Dispersion of heat at the spreader (base plate) is extremely important for the heatsink. If heat is not spread at the base plate, even the best fins will not be able to reach their true performance.

In the same way that the thermal performance of fins is

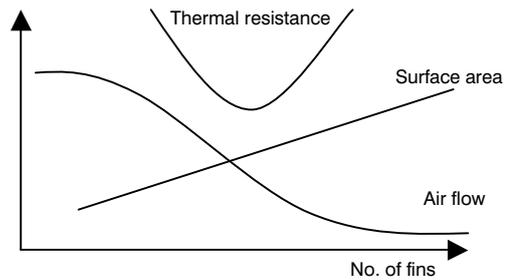


Figure 9 Relationship between number of fins and thermal resistance.

shown by fin efficiency, we have defined spread efficiency.

Comparing with fin efficiency:

- Fin efficiency is average temperature for the fins as a whole (one dimension) / temperature at fin base
- Spread efficiency is average temperature for the base plate (2 dimensions) / temperature of exothermic device thereby effecting an extension from 1 dimension to 2.

Like fin efficiency, spread efficiency takes a numerical value from 0 to 1, the larger the number the more the heat spreads to the edges.

Extending to 3 dimensions, heatsink efficiency (3 dimensions) is represented by heatsink efficiency = spread efficiency × fin efficiency, and for the thermal performance of the heatsink as a whole we have: fin area × heatsink efficiency = fin area × spread efficiency × fin efficiency.

What is needed is to raise fin area × spread efficiency × fin efficiency in proper balance, while paying attention to pressure loss. With HIEROH it becomes possible to achieve this with a single software package.

### 4.2 Optimization at Constant Height

In cases in which the dimension in the direction of fin height is limited, the question of how thick the base plate should be is a difficult one.

Figure 10 shows a typical representation. Care must be exercised, since if the base plate is too thin the spread in the base plate is poorer and thermal resistance tends to increase precipitously.

With HIEROH, under conditions where total height (fin height + base plate height) is constant, it is possible to

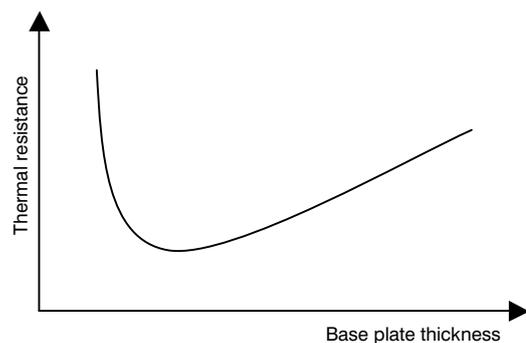


Figure 10 Relationship between base plate thickness and thermal resistance.

determine the minimum value for thermal resistance by changing base plate height (and obviously fin height as well) as parameters. Here also higher speed is achieved.

#### 4.3 Heatpipe Effect

A heatpipe may be used in common on the base plate when adequate heat dissipation cannot be obtained without a heatpipe, and in such cases it is possible to make a rough estimate of the effect.

An algorithm is applied that includes empirical parameters from experimental values. This would be:

HP (ordinary):	Number of heatpipes :	1 or 2
HP (superior):		: several
HP (best):		: as many as can be inserted

## 5. CONCLUSION

- Adopting a hybrid analog + digital structure has made it possible to achieve simple operation as well as speedy analysis.
- Using spread efficiency as a design guideline for optimization has made optimization easier.
- It is also possible to calculate estimated values in cases when heatpipes are inserted into the base plate.
- As part of a total thermal solution, extending from design to finished product, we hope to use HIEROH to speed up the design process as well as to assist in upgrading customer service.

## ACKNOWLEDGMENTS

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