THERMAL DESIGN OF A DISK-ARRAY SYSTEM

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ABSTRACT

A procedure for solving the thermal problems of a fan-cooled disk-array system is developed for industrial application. The procedure requires both the measurements of the temperatures of key components at various air flow rates across a single hard-disk and the computational simulations of isothermal flows for a preliminarily designed mechanical configuration of a system by employing a commercial CFD software package. The flow rate and pressure drop of the air stream across a single-disk are measured with an AMCA 210 flow bench. The temperatures of the components are detected by the fine-wire thermocouples. The methodology of the development of the disk array and the like is illustrated by an example. The results show that the single-disk experiment can provide the designer to determine the air flow rate for desired operation temperatures of key components. The calculated flow rate and pressure drop can be used to match selected fans to the system. The prediction correlates well with the experimental values. The calculated flow patterns can be used to improve the preliminary design of the system mechanical configuration.

KEY WORDS: fan matching, thermal design, disk array

NOMENCLATURE

d	spacing between hard disks when installed in stack, mm
n	number of hard disks integrated in system
P_{atm}	atmospheric pressure, kPa
ΔP	pressure difference developed by fan or across a disk/system, mmAq
Q_t	total air-flow rate of system $= Q_d \times n$, m ³ /s
Q_d	air-flow rate across a single disk, m ³ /s
T_{atm}	atmospheric temperature, °C
T_1-T_5	temperatures of key components of target hard-disk, °C
$T_{1m}-T_{5m}$	maximum allowable temperatures of key components of target hard-disk, °C
$T_{1,e}-T_{5,e}$	expected operation temperatures of key components of target hard-disk, °C

Greek symbols

ρ	mass density of air, kg/m ³
ϕ	porosity of front panel, void area divided by total area of front panel

INTRODUCTION

Heat transfer engineering is playing an increasingly important role in the advancement of electronics technology because the cooling problems in electronic equipment are strongly coupled with considerations of electronic performance. Because the electronic devices are widely applied in industries, operation in hostile environments is inevitable. One of the most encountered problems, which affect the reliability of the electronic devices, is the difficulty of heat dissipation. In general, the heat transfer problems of electronics technology can be classified into four categories: the chip (package, component), device (cooler, heat sink), board, and system levels. Characteristics of problems and solution methods provide wide range of choices for each category, depending on factors like power dissipation, geometry, scales, noise level, cost, fabrication, marketing, etc.

Extensive research on the heat transfer problems of the chip level has been conducted during the past two decades with new materials and structures to house chips of an increasing numbers of input/output terminals in a package, to shorten the interconnection distances among various levels of electronic circuits, to improve the electrical characteristic, such as impedance to the transmission of high frequency signals, and to reduce the cost of fabrication. References can be found in, for instance, Kraus and Bar-Cohen [1] and Nakayama [2]. The advent of modern high speed central processing unit of the computer creates serious problem of more-than-40 watts thermal dissipation. Device-level research like heat sinks and fins [3-8] using conventional convective heat transfer principle may not be enough. Devices using phase-change principle have attracted lots of notices [9-14]. The problems of board-level heat dissipation have been studied by many investigators [15-21]. Most of the issues were concerned with the effects of aerodynamics on the heat transfer of various arrangements of components on the circuit board.

Studies on the cooling problems of electronic systems can be found mostly on the personal computers, notebook computers, and the like [22, 23]. For power supplies, network servers, disk arrays, etc, which require special design of mechanical configuration, the design and solution algorithm for cooling purpose were not well documented because complex fluid flows and heat transfer phenomena usually came up. Computer software simulation method was traditionally employed as the preliminary design tool. Because

the complexity of flow passages and varieties of electronic components, devices, boards, etc., detailed computer simulation coupling the flow and heat transfer seems impractical. It is apparent that simplification must be made. For instance, the "thermal network" model [24], which was one of the simplified simulation methods, was effective for preliminary design of an electronic system. However, the advances of the electronic system using high power-dissipation components in a compact space necessitate a quick, complete, and reliable design procedure. This paper reports an algorithm of combining a simple single-disk experiment and a cold-flow computational simulation for the design of a disk-array system. The developed algorithm can be applied to similar systems.

THE TASK AND STRATEGY

The aim of a thermal design of a disk-array system is to keep the temperature of each key component of all hard disks installed in the system lower than the specified maximum temperature. To achieve such a goal, most intuitive idea is to employ a commercial computational fluid mechanics (CFD) code (e.g. FLOTHERM, ANSYS, IDEAS ESC, ICEPAK, etc.) to solve simultaneously the continuity, momentum, and energy equations for the velocity and temperature fields in a pre-designed system. This direct method, however, requires designers to input hundreds of physical, thermal, and power-consumption properties as well as the parameters for each electrical/non-electrical component to construct the model for computation. Many of these properties and parameters may not be available or easily obtainable. Even that the properties and parameters are available, for most of the detailed system-level simulation, the execution of computation may last for an unexpected long time and come out to an incorrect result. In most cases of complex systems, the calculations are not able to complete without large compromise in the simplification of

simulation seems to be impractical at this stage of CFD development. An indirect but efficient approach must be sought.

In using the "thermal network" method to solve the cooling problem of an electronic system, Jokinen and Saari [24] has proposed that if the power consumption in a system is not extremely high, an isothermal flow computation is enough to simulate the hot flow field without significant deviation. Experiments conducted by the present authors show that the pressure drops at various flow rates in both the cases of the isothermal and hot target disks installed in an enclosing channel are almost similar, as shown in Fig. 1. Estimation using the theoretical consideration of energy balance [25], 10°C of temperature increase in the cooling air may cause at most approximately 3% of pressure drop. This pressure-drop induced by the increase of internal energy will be counter-balanced by the pressure-increase induced by the addition of heat to the air flow from the electronics. Therefore, using an isothermal-flow simulation may be an appropriate substitute to a hot-flow computation to obtain the flow field and pressure drop of an electronic system. Since the simulation of an isothermal system is much easier than a temperature-varying one, matching fans to a system using the calculated isothermal flow and pressure loss data should be feasible. However, without coupling the energy equation there will be no solutions for individual component temperatures. Prediction of an overheat design thus becomes impossible.

In order to overcome the difficulty of temperature prediction, a single-disk experiment is conducted to obtain temperatures of the key components of the hard disk at various air flow rates. The proposed methodology for design of the target system is shown in Fig. 2. A preliminary design of the system mechanical configuration based on the fundamental

Fig. 1 Comparison of pressure drops of hot and isothermal flows passing a hard disk. $T_{atm}=25^{\circ}\text{C}$ and $P_{atm}=101.2\text{kPa}$. Data measured with an AMCA 210 flow bench.

modeling and the architecture of the system. With large simplification in modeling, component arrangement, and mechanical configuration, the computational results, particularly the temperature field, would usually deviate drastically from the practical values. Therefore, the direct

Fig.2 Flow chart for thermal design of disk array systems.

knowledge of the engineering fluid flow and heat transfer as well as the collected data base is required. An experiment measuring temperatures of the key components at various air flows with a simulated turbulence level passing through a pre-designed channel geometry and going across a single hard-disk is conducted. Relationship between the temperature of individual key electronic component and the flow rate of cooling air is obtained. By considering the allowable maximum temperatures of the key components and fan performance, a target air flow rate and the operation temperatures of key electronic components are pre-determined.

There are two methods to match cooling fans to the system to achieve desired air flow rate. The first is to conduct a computational simulation of several air flow rates of isothermal flows for the preliminarily designed system by employing a commercial CFD software package to obtain a system impedance curve which is a relation between the pressure loss and flow rate. The system impedance curve can be matched to a fan performance curve of existing fans to locate an operational flow rate and pressure difference, which would be developed by the fan. The located operational flow rate must be greater than the pre-determined air flow rate for desired temperatures of key components. If not, a new fan performance curve can be used to match again until the flow rate is satisfied. The second method is to engage an existing fan performance curve to the pre-designed system to calculate the isothermal flow field by using a CFD software. Automatic iterative computations may approach an operational flow rate and pressure difference of the selected fan. The calculated operational flow rate must be greater than the pre-determined air flow rate for the desired temperatures of key components. If not, a new fan performance curve can be used to match or compute again until the flow rate is satisfied.

The software-calculated flow patterns represented by the velocity distributions can be used to improve the preliminary design of the system mechanical configuration. Once the design is modified, the fan can be matched again by using either one of the above-mentioned fan-matching methods. The procedure of using the results of the single-disk experiment and the isothermal flow computation is practically verified in the following example.

AN EXAMPLE

An example of the design procedure for a disk-array system using the developed algorithm is shown in the following sections. Eight SCSI hard disks, each has a storage capacity of 9.1GB and a maximum rotation speed of 10000 rpm, are to be integrated in a system. The average power dissipation is about 12 watts when a single disk is performing random read/write operations.

Design of disk bay

Figure 3 shows the layout and dimensions of the target disk. From the specifications of the target hard-disk, temperatures of four chip-components and one HDA check point denoted by T_1 , T_2 , T_3 , T_4 , and T_5 must be kept under the allowable maximum values, $T_{1,m}$, $T_{2,m}$, $T_{3,m}$, $T_{4,m}$, and $T_{5,m}$, respectively, as shown in Fig. 3. The hard disk has to be installed in a bay, as shown in Fig. 4, before inserted into a system casing. In the

preliminary design, eight disk bays will be stacked from the

Fig. 3 Layout of target hard-disk and limits of key electronic components.

bottom to the top and placed in the front part of the system casing. Cooling air is to be drawn through the slotted front panels of the disk bays by using exhaust fans installed in the rear panel of the system casing. The cooling air passing over the hard disks installed in the bays must have enough velocity to keep the temperatures of the key components under the allowable maximum values. If a flow rate is determined for

Fig. 4 Bay and hard disk design.

safety operation, the spacing d between disks must be

considered for low pressure drop in order to optimize the fan performance. A spacing-varying experiment was performed by the authors and a minimum value of about 10mm is found to avoid drastic increase of pressure loss. In this example, a spacing of 12mm between disks is designed.

Another factor, which may cause significant pressure loss is the porosity ϕ of the front panel. The authors have conducted CFD computations for pressure drop of flows passing through the slotted front panel for various porosities with or without an EMI protection grate installed 10mm downstream the front panel. The EMI protection grate is a slotted thin metal plate, which is commonly placed in front of the hard disk to reduce the influences of radio emissions on the disk operation. Critical porosity values 22% and 33% are found for the cases with and without an EMI grate, respectively. If the porosity is lower than the critical value, the pressure loss increases abruptly. Both the vertical and horizontal slot designs show the same results. In this example, a 33% porosity is used for the vertical slotted front panel with an EMI protection grate. The slotted front panel has an effect of generating turbulence in the air flows, which may increase heat transfer when the flows pass over the disk. The authors have conducted an experiment for the comparison of the key-component temperatures of a hard disk with and without a slotted front panel at various flow rates. The 33% porosity front panel causes averagely 2 to 4°C decrease of the key-component temperatures compared with those without a front panel.

Determination of flow rate

In order to determine the air flow rate for safety operation of the disk array, a single-disk experiment is performed via a setup shown in Fig. 5. A hard disk is clamped laterally from

Fig. 5 Experimental setup of single-disk experiment.

two sides in a rectangular acrylic channel. The upper and lower spacing is 12mm. Two 33% gratings are attached to the front opening of the acrylic channel to simulate the real situation. The disk is powered to perform random read/write operations. The acrylic channel is attached to an AMCA 210 flow bench [26], which serves as a device for the measurement of flow rate. The cooling air is drawn into the acrylic channel by a suction fan, which is attached to the AMCA 210 flow bench. Steady state temperatures of the key-components of the hard disk are measured with five T-type thermal couples glue-

attached to the surfaces of key components.

The results obtained at $T_{atm}=25^{\circ}\text{C}$ and $P_{atm}=101.2\text{kPa}$ are shown in Fig. 6. Apparently, temperature of each key-component decreases with the increase of air flow rate. The

Fig. 6 Temperatures of key components obtained from single-disk experiment. $T_{atm}=25^{\circ}\text{C}$ and $P_{atm}=101.2\text{kPa}$.

filled symbols denote the allowable maximum temperatures of key components. In practical use, $Q_d=0.001\text{m}^3/\text{s}$ can be taken as a critical flow rate for a single disk, below which the normal operation may not be expected. Because the inlet air temperature in practical application may exceed the normal value, and also because lower component temperatures may extend the life period of the disks, much higher flow rate than the critical value should be used. In other words, the critical system flow rate should exceed $Q_s=8 \times Q_d=0.008\text{m}^3/\text{s}$.

Preliminary design of system configuration

Figure 7 shows the preliminary design of the system mechanical configuration. The casing of the system has a rectangular cross section. Eight hard disks are stacked vertically in the front part of the casing, as shown in Fig. 7(a).

Fig. 7 Preliminary design of system mechanical configuration.

The power supplies which have an independent cooling system are placed at the isolated bottom box. A back circuit-board and a metallic holding plate are installed vertically behind the disk stack, as shown in Figs. 7(b) and (c). The hard

disks and bays can slide into the system casing so that the small circuit boards at the rear ends of the hard disks can be inserted into the adapter slots of the vertical circuit board. Three axial-flow fans are to be installed on the rear panel to enable the air flows to go from the front panel, pass through the disk surfaces, and ventilate eventually through the rear panel, as shown in Fig. 7(b). This mechanical configuration may not be a good design for the consideration of low flow-resistance because a large pressure loss induced by the vertical back plates would be expected. Also, a recirculation area would be formed behind the back plates. The momentum of reverse flows and induced low pressure would certainly cause a deterioration of fan performance. It is, however, a typical example for illustration.

Isothermal flow simulation using a CFD code

As mentioned in the strategy, two methods can be used to match cooling fans to the system to achieve the desired air flow rate. The first is to conduct a computational simulation of several air flow rates of isothermal flows for the system to obtain a system impedance curve, then match the calculated system impedance curve to a performance curve of three fans in parallel arrangement to locate the operational flow rate and pressure difference. The second method is to engage an existing performance curve of three fans in parallel arrangement to the system to calculate the isothermal flow field by using a CFD software. Using automatic iteration, it may approach the operational flow rate and pressure difference of the selected fans. A traditionally used $k-\epsilon$ turbulence model is employed in the computation. Take three Delta AFB0812H fans in parallel for calculations, the results are shown in Fig. 8. The fan curve extends from the upper-left corner to the lower-right corner of Fig. 8. The calculated

Fig. 8 Matching of fans. $T_{atm}=25^{\circ}\text{C}$ and $P_{atm}=101.2\text{kPa}$.

system impedance curve obtained from the first method intersect the fan performance curve at $Q_f=0.0215\text{m}^3/\text{s}$ and $\Delta P=2.25\text{mmAq}$. The operation point obtained by using the second method approaches to a point at $Q_f=0.0225\text{m}^3/\text{s}$ and $\Delta P=2.13\text{mmAq}$. Comparing the calculated system flow rates with the critical flow rate $Q_f=0.008\text{m}^3/\text{s}$, it seems to be an over design if the present set of fans is matched to the system.

Experimental verifications

In order to verify the effectiveness of this procedure, a prototype system is built. The prototype system is installed with three Delta AFB0812H fans in parallel arrangement. Figure 9 shows the experimental setup. The prototype system

Fig. 9 Experimental setup for prototype system.

was connected to the AMCA 210 flow bench through a contraction section. By attaching fine-wire thermal couples to the key components of the hard disks, performing random read/write operations, and regulating the revolution speed of the suction fan of the AMCA 210 flow bench so that the pressure of the first chamber of the flow bench equals to the atmospheric pressure, the flow rate of the system and the temperatures of the key components are measured.

The measured system flow rate is $Q_f=0.02\text{m}^3/\text{s}$, corresponding to a pressure drop $\Delta P=2.3\text{mmAq}$, as shown in Fig. 8. The calculated air flow rates using the first and second methods deviate approximately 7.5% and 12.5% from the measurement value $Q_f=0.02\text{m}^3/\text{s}$, respectively. The pressure deviations are about 2.2% and 7.4%, respectively. The predictions are in acceptable range for practical engineering applications.

Table 1. Comparison of temperature of key components between prototype system and single disk experiments.

		T_1 ($^{\circ}\text{C}$)	T_2 ($^{\circ}\text{C}$)	T_3 ($^{\circ}\text{C}$)	T_4 ($^{\circ}\text{C}$)	T_5 ($^{\circ}\text{C}$)
Prototype system experiment $Q_f=0.02\text{m}^3/\text{s}$	Disk #3	44.6	38.5	44.6	41.0	34.2
	Disk #5	45.5	39.3	45.9	42.0	35.1
	Disk #7	45.8	39.6	46.0	42.2	35.2
Expected temperature from single disk experiments $Q_d=0.0025\text{m}^3/\text{s}$		44.9	38.2	45.3	41.1	34.3

Selected temperature results are shown in Table 1. The system flow rate $Q_f=0.02\text{m}^3/\text{s}$ corresponds to an average single-disk flow rate $Q_d=0.0025\text{m}^3/\text{s}$. From Fig. 6, the expected operation temperatures $T_{e,1} \sim T_{e,5}$ of the key components would be 44.9, 38.2, 45.3, 41.1, and 34.3 $^{\circ}\text{C}$, respectively. It is apparent that the component temperatures of

the prototype system operated at $Q_f=0.02\text{m}^3/\text{s}$ are well correlated with those obtained from the single disk experiment at $Q_d=0.0025\text{m}^3/\text{s}$. A general difference within $\pm 1^\circ\text{C}$ is observed. Another operation point at lower flow rate is checked. One of the three fans installed in the prototype system is removed so that only two fans participate in the operation. The system flow rate Q_f reduces to $0.0148\text{m}^3/\text{s}$, corresponding to an average single-disk flow rate $Q_d=0.00185\text{m}^3/\text{s}$. The measured component temperatures are shown in Table 2. The component temperatures of the system experiment deviate insignificantly from those of the single-disk experiment.

Table 2. Comparison of temperature of key components between prototype system and single disk experiments.

		T_1 ($^\circ\text{C}$)	T_2 ($^\circ\text{C}$)	T_3 ($^\circ\text{C}$)	T_4 ($^\circ\text{C}$)	T_5 ($^\circ\text{C}$)
Prototype system experiment $Q_f=0.0148\text{m}^3/\text{s}$	Disk #3	48.9	42.7	47.5	44.7	37.7
	Disk #5	49.5	43.0	47.9	45.3	37.9
	Disk #7	49.2	42.9	47.6	44.9	37.7
Expected temperature from single disk experiments $Q_d=0.00185\text{m}^3/\text{s}$		47.8	40.4	48.0	43.4	36.6

Calculated flow patterns

Fig. 10 Flow pattern shown by velocity vectors on horizontal cross-section across $0.5d$ plane above fifth disk. $Q_f=0.0272\text{m}^3/\text{s}$, $P_{atm}=101.3\text{kPa}$, $T_{atm}=25^\circ\text{C}$.

Flow patterns shown by the calculated velocity vectors can be used for the modification of the system configuration. For example, the flow pattern on the plane $0.5d$ above the component side of the fifth hard disk shown in Fig. 10 presents a negative effect of the back plates. The flows around the rear part of the hard disk do not go straightforward. The

ventilation holes of the back plates can be modified to correct this flow pattern. A recirculation bubble can be found around the left rear space behind the back plates, which indicates a modification is necessary if the pressure loss is to be reduced. The flow pattern on the vertical plane across one quarter of the system width shown in Fig. 11 presents clearly the recirculation problems induced by the back plates. Because a large pressure loss induced by the three-dimensional recirculation is expected, the back plate design can be re-considered.

Fig. 11 Flow pattern shown by velocity vectors on vertical plane across one quarter of the system width. $Q_f=0.0272\text{m}^3/\text{s}$, $P_{atm}=101.3\text{kPa}$, $T_{atm}=25^\circ\text{C}$.

CONCLUSIONS

Methodology of matching the cooling fans to a disk-array system to solve the thermal problems is developed for industrial applications. Practical verifications have proven the appropriation and effectiveness of this approach. An experiment measuring temperatures of the key components at various air flow rates across a single hard-disk as well as a computational simulation of isothermal flows for a preliminarily designed mechanical configuration of a system are required. Results of the single-disk experiment enable the designer to determine the air flow rate for desired operation temperatures of the key components. The calculated flow rate/pressure drop curve of the system can be matched to the fan performance curves of existing fans. Alternatively, by engaging an existing fan performance curve to the pre-designed system and conducting automatic iterative calculations of isothermal flows by using a CFD software, the operational flow rate and pressure drop may be obtained. The calculated operation flow rate must be greater than the pre-determined air flow rate for desired temperatures of key components. If not, a new fan performance curve can be used to match or compute again until the flow rate is satisfied. The

software-calculated flow patterns can be used to modify the configurations of the flow passages to reduce system pressure drop and/or recirculation areas, which usually lead to local high temperatures and extra consumption of the fan power.

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