XIIIth International Symposium on High Voltage Engineering, Netherlands 2003, Smit (ed.)
© 2003 Millpress, Rotterdam, ISBN 90-77017-79-8

Corona driven air propulsion for cooling of electronics

F. Yang, N.E. Jewell-Larsen, D.L. Brown, K. Pendergrass, D.A. Parker, I.A. Krichtafovitch*, A.V. Mamishev
Department of Electrical Engineering, University of Washington, Seattle, WA 98105, USA
*Chief Scientific Officer, Kronos Air Technologies, Redmond, WA 98052, USA

Abstract: The possibility of building a high voltage electrostatic air pump for cooling of microelectronics is investigated. Existing cooling technology no longer provides adequate heat dissipation due to excessive heat generation caused by the growing component density on electronic devices. Heat sink fins are packed more closely to increase the heat exchange surface area, resulting in narrower channels between the fins. Air viscosity in narrow channels reduces the cooling efficiency of the heat sinks. Electrostatic air propulsion methods may improve airflow patterns in narrow channels. Several prototypes of the electrostatic air pump were built. Corona onset voltage was measured, and the current-voltage relationship showed a positive exponential relationship. The performance of the corona pump displayed a nearly linear voltage-air velocity relationship, a logarithmic decrease in air gap impedance between corona and collector electrodes, and a departure from classic air velocity profiles. Energy efficiency of the proposed approach is shown to be comparable to that of existing technology.

Introduction

Improvements in the cooling capacity of conventional rotary fans have stagnated due to the increasing fluid viscosity as the channels between heat sink fins become narrower [1]. Dynamic velocity profiles, comparable air velocity, and a decreased boundary layer make corona pumps a viable alternative to conventional methods of microelectronic cooling.

Liquid cooling is a prevalent alternative process that has been researched for improved convection in heat pipes [2] and micro-channels [3]. Recently, this process has found commercial applications, for example, in IBM's Think Pad laptop line. The advantage offered by liquid coolants is their high specific heat, which enables an intensive thermal transfer out of a system with a relatively small increase in coolant temperatures. This advantage must be weighed against the need for exotic high dielectric fluids for insulation [3] and structures for fluid containment. The corona air pump increases the potential thermal transfer of the device, while maintaining air as the coolant

In the present study, corona discharge is utilized as the driving mechanism for a high air velocity electrostatic pump. A corona pump prototype was fabricated for analysis and optimization of electrical characteristics and airflow profiles.

Figure 1 illustrates the operation of this device. Gas molecules surrounding the corona electrode are ionized by the high intensity electric field at the tip, forming an ion stream between the corona and collector electrodes, thus creating airflow [4].

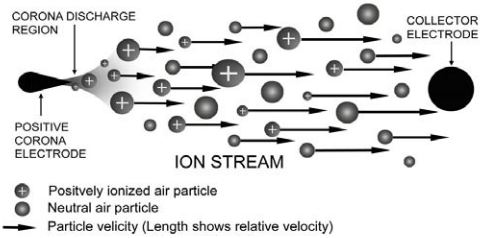


Figure 1: Ion stream of a DC electrostatic air pump, where the corona and collector electrodes are powered by a high voltage DC source.

Ultimately, corona pumps allow for airflow generation with low noise, static filtration [5], air sterilization [6], and no moving parts. These ideal characteristics of corona air pumps give rise to a variety of applications as air handling systems.

The principle of ionic air propulsion with corona-generated charged particles has been known nearly as long as electricity [4]. One of the first references to sensing moving air near a charged tube appeared 300 years ago in a book by Francis Hauksbee [7]. Many pioneers of electricity, including Newton, Faraday, and Maxwell, studied this phenomenon. Later studies determined corona onset voltage to be a function of the corona wire diameter and composition, air temperature, and pressure [8]. As the demand for enhanced cooling grows, corona driven electrostatic air pumps continue to be investigated for improved thermal transfer [9].

This study includes an analysis of the airflow and dielectric properties of a corona air pump. It also describes the current-voltage relationship, voltage-air velocity relationship, airflow profiles, and corona-collector separation impedance. Finally, corona pump efficiency is compared to rotary fan efficiency.

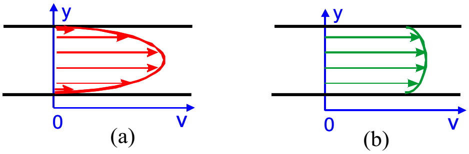
Device Description

Columbic force interactions between the ions and the electric field are responsible for ion acceleration. An ionic flow is propelled with columbic force rather than backpressure, making it possible to define the airflow profile within the duct by controlling the electric field geometry and intensity. Such control permits maximization of airflow and cooling efficiency.

Ideally, forced convection heat transfer near a parallel plate of area A is described by the relationship

$$Q = hA(T_w - T_b) \quad (1)$$

where Q is the thermal energy transfer, h is the convection heat transfer coefficient, which is proportional to the square root of the air velocity through the channel, T_w is the temperature of the wall, and T_b is the average fluid temperature [10]. The proportionality between Q and h becomes important when comparing corona flows and pressure driven flows. Figure 2 displays, (a), an airflow profile from a pressure differential flow along a duct wall and, (b), an idealized airflow profile along a duct wall from a corona-driven ionized flow. The corona-driven flow can ensure a greater speed close to the wall than a pressure differential flow, due to the continual columbic force being applied to fluid through the duct. The higher fluid velocity at the wall effectively decreases the boundary layer at the solid-fluid interface allowing for more effective cooling. Strictly speaking, both profiles are more complex and not completely laminar, but the analysis of secondary effects is beyond the scope of this paper.



(a) (b)

Figure 2: Idealized airflow profiles from (a) a pressure differential and (b) a corona-driven air pump.

To achieve maximum airflow efficiency from a corona-driven flow, an electrode configuration creating an electric field running parallel to the channel walls is needed to minimize losses from ion collisions into the sidewalls. Ultimately, the optimization of electric field distribution requires numerical modeling of space charge effects and fluid dynamics. This paper, however, presents results achieved with preliminary experimental optimization results using parametric sweeps of device geometry and material properties.

It is possible to achieve a parallel electric field by using distributed electric potential collector electrodes, which were investigated in this study. The electrodes were built using semi-conductive carbon-doped polyimide Kapton to form a constant voltage gradient along the collector displayed in Figure 3. The voltage distribution along the electrode is not only a function of surface conductivity, but also a function of space charge dynamics and hence of the ionic current distribution in the volume of the device. The model includes two collector electrode sheets symmetrical with respect to the razor-like corona electrode and tapering towards the vertical axis.

The corona electrode was constructed from a high carbon steel razor, which provides a consistent tip diameter along its length. Teflon support bars (Figure 3, T) insulate the collector electrodes from the device stand and provide a mechanical connection to the xyz-translation table for micro precision placement.

All data presented in this investigation is produced with the experimental setup displayed in Figure 4, which uses a semi-conductive *20 µm* Kapton film for the collector electrode.

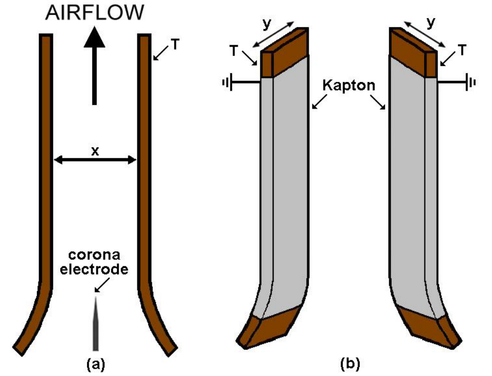
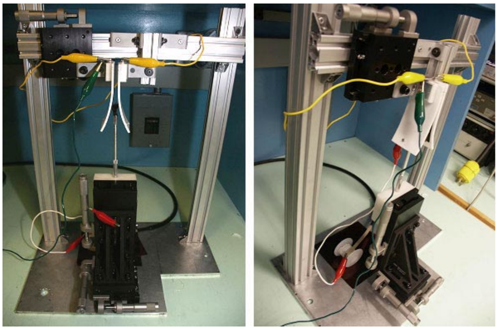


Figure 3: (a) side view of the corona pump structure; (b) continuous voltage gradient is generated with a semi-conductive Kapton film.



(a) (b)

Figure 4: Front view (a) and side view (b) of the experimental setup using semi-conductive Kapton as the collector electrode.

Experimental Results

Corona onset voltage

Figure 5 shows the measured *I-V* characteristic of the corona air pump. Beyond corona onset voltage, occurring at 5.2 kV, a collector current (I_c) is detected flowing from the corona electrode to the collector electrode. In accordance with classical theory, I_c increases exponentially with the corona voltage (V_c), corresponding to a logarithmic decrease in air resistance [4].

Air velocity was measured using a VELOCICALC PLUS 8386 airflow sensor. Figure 6 shows a detected measurable airflow beyond corona voltage (V_c) of 6 kV and air velocity (v_a) increased linearly with V_c at a slope of 1.5 up to the 9 kV potential and decreased to a slope of 0.5 above 9 kV. Stable peak air velocity was limited at a V_c of 11 kV due to dielectric breakdown at higher potential differences. The v_a vs. V_c relationship shown in Figure 6, Figure 7, and Figure 8 was achieved using semi-conductive Kapton collectors, which generate a non-optimized linear voltage gradient due to the inherent fixed continuous voltage drop across the film. The optimized surface conductivity distribution will eventually allow for higher air velocities, by generating more efficient flows.

The air velocity profile shown in Figure 7 was measured in the y-direction across the collector electrode outlet represented in Figure 3. Two peaks are detected along the outlet approximately inline with the corners of the corona electrode. These peaks are due to increased ion generation at the two corners caused by an increase in field intensity from the sharp corners.

Figure 8 illustrates an air velocity profile that was obtained from measuring the air velocity across the x-separation shown in Figure 3. At the center of the outlet separation, the airflow reached a maximum velocity of 4 m/s, or 800 linear feet per minute (lfm). This flow rate is one and a half to two times greater than that of conventional CPU muffin cooling fans, as seen in Table 1. Airflow measurements were taken at the top of the channel, four and a half centimeters upstream from the point of ion recombination, resulting in an airflow profile measurement showing significant air resistance at the sides and corresponding lower air velocities. Work is being done to decrease the channel length and see if it results in an improved air velocity profile. An investigation is also being conducted to enable dynamic collector voltages. The dynamic voltage control is used to realize optimized voltage distributions, determined by Ansoft Maxwell software simulations. Optimized voltage distributions will increase the ion acceleration period and inter-channel airflow control allowing for a more uniform airflow profile across the channel.

Energy Efficiency

By dividing the airflow rating in cubic feet per minute (CFM) by the power consumption in watts, the pump efficiency can be determined. Following this definition, Figure 9 relates the corona voltage (V_c) to the pump efficiency. Airflow ratings were calculated from the peak air velocity multiplied by the cross-sectional area of the aperture.

Efficiency reached a maximum at low air velocities and decreased exponentially with V_c. Pump efficiency approaches a limit of 0.3 CFM/W at 11 kV. Advancements raising the breakdown threshold may allow for increased air velocities with minimal loss of pump efficiency.

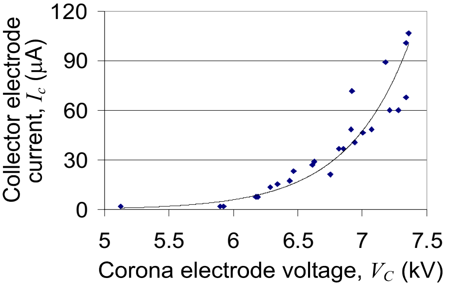


Figure 5: Measured corona voltage V_c versus collector electrode current I_c exhibits an exponential dependence of approximately $3\times10^{-5}\,e^{2V_c}$.

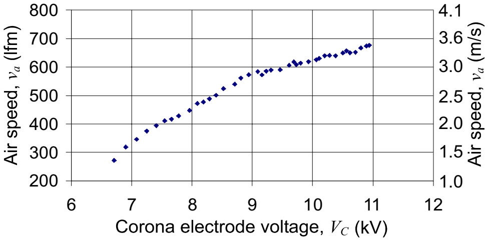


Figure 6: Measured corona voltage V_c versus air speed v_a at the outlet.

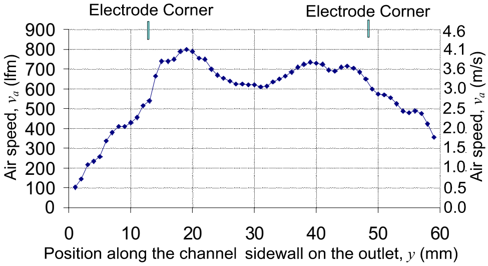


Figure 7: Air speed profile along the sidewall from the outlet.

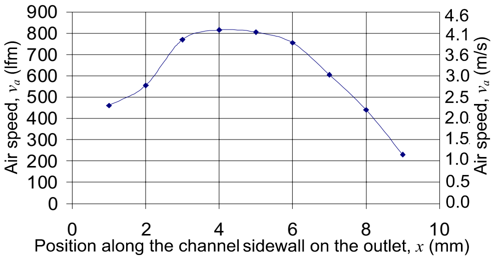


Figure 8: Air speed profile across the 8 mm separation of the collector and electrode outlet.

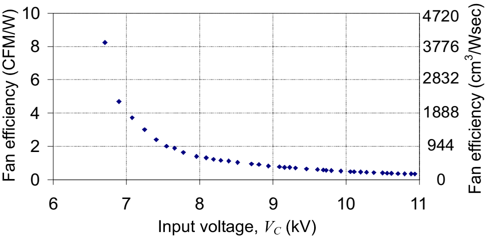


Figure 9: Pump efficiency as a function of input voltage (V).

Traditional computer cooling fan efficiency ranges from three to eight CFM/W at various air velocities [11] as shown in Table 1. The corona air pump fabricated in this investigation lies within the range of efficiency for conventional fans while offering higher air velocities.

Table 1: CPU rotary fan airflows and efficiencies.

Pentium CPU fan	**Fan Dia. (mm)**	**Airflow (lfm / m/s)**	**Efficiency (CFM/W)**
K1 for PII	40	370 / 1.9	3.79
M1 for PII & PIII	50	568 / 2.9	6.67
Cool 1U for PIII	50	663 / 3.4	7.78
Cool 1U-478 for P4	60	559 / 2.8	4.89

Further research will optimize the airflow efficiency at the macro scale for later conversion to a MEMS level. A preliminary investigation is being conducted for a MEMS level design. Future steps will focus on new electrode configurations and materials to increase the breakdown threshold.

Conclusions and Future Work

This study explores the possibility of building an electrostatic air pump for enhanced heat withdrawal from microelectronic devices and MEMS. Corona-driven air pumps may serve as a catalyst for the next generation of high-density microelectronics. The main advantages of a corona driven pump over a rotary fan are the elimination of moving parts, low noise, dynamic airflow profiles, versatile shapes and sizes, and compatibility with chip and chip-level structures. Channel device geometry with a razor corona electrode is found to be a promising design for heat removal. A prototype air pump of this kind has been built at the macro-scale for analysis of electrical and airflow properties. Experiments showed a near linear relationship between corona voltage and air velocity. Collector electrode current grew exponentially with increasing voltage beyond the 5.2 kV corona onset voltage. At the center of the aperture separation, the airflow reached a maximum of 4 m/s at 11 kV, beyond which dielectric breakdown occurred. The prototype electrostatic air pump efficiency was comparable to that of conventional rotary CPU cooling fans. At higher air velocities, the device efficiency approached a limit of 0.3 CFM/W.

Future research directions include optimization of geometry and driving electronics; system integration; numerical simulation of the electrodynamics of moving media and space charge on a micro-scale; and micro-scale fabrication.

Acknowledgments

The authors appreciate the scientific and technical leadership and extensive help of Kronos Air Technologies. Financial support has been provided by the Royalty Research Fund of the University of Washington, and the American Public Power Association Demonstration of Energy-Efficient Developments Program. Undergraduate research scholarships were funded by the University of Washington Mary Gates Research Training Grant, the Washington NASA Space Grant Consortium, and the Grainger Foundation. The donation of Ansoft Maxwell for simulations is greatly appreciated.

References

[1] B. Gromoll, "Advanced Micro Air-Cooling Systems for High Density Packaging," *Proceedings of 10th Semiconductor Thermal Measurement and Management Symposium*, 1994, pp. 53-58.

[2] J. Xie, A. Ali, and R. Bhatia, "The Use of Heat Pipes in Personal Computers," *The Sixth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*, 1998, pp. 442-448.

[3] A. E. Bergles, *Heat Transfer in Electronic and Microelectronic Equipment,* Troy, NY, Hemisphere Publishing Corporation, 1990.

[4] M. Robinson, "Movement of Air in the Electronic Wind of Corona Discharge," *AIEE Transactions*, vol. 80, pp. 143-150, May 1961.

[5] K. J. Mclean, "Electrostatic Precipitators," *IEE Proceedings on Science Measurement and Technology*, vol. 135, no. 6, pp. 347-361, July 1988.

[6] M. Jyumonji and H. Uchiyama, "Field Experiment on the Abatement of Stock-Raising Odors by an Electrostatic Fog-Liquefier," *Journal of Electrostatics*, vol. 40-1, pp. 645-650, June 1997.

[7] F. Hauksbee, *Physico-Mechanical Experiments on Various Subjects,* London, England, 1709, pp. 46-47.

[8] F. W. Peek, *Dielectric Phenomena in High Voltage Engineering,* New York:McGraw-Hill, 1929.

[9] J. Mathew and F. C. Lai, "Enhanced Heat Transfer in a Horizontal Channel With Double Electrodes," *IEEE Industry Applications Conference*, vol. 2, 1995, pp. 1472-1479.

[10] J.P.Holman, "Principles of Convection," *Heat Transfer* 8th ed. 1997, pp. 241-261.

[11] PC Power and Cooling, Inc., "Rotarty fan efficiency for Intel proccesor fans," Jan. 2002. www.pcpowercooling.com/products/cooling/cooling.htm.