

A THERMOELECTRIC-BASED FORCED-AIR DELIVERY SYSTEM TO INDUCE CONTROLLED CHANGES IN BODY TEMPERATURE

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INTRODUCTION

Recent research findings in neuroanesthesia and critical care medicine have motivated the development of a forced-air cooling system that can effectively provide controlled, mild hypothermia in an anesthetized patient. The primary benefit of mild hypothermia is to decrease both tissue metabolic rate and oxygen consumption during impairment of tissue blood supply (Sessler 1990). Mild hypothermia (33-36°C) can confer significant protection to the central nervous system during cardiac and carotid surgeries, ischemic or hypoxic insults, neurosurgery, and to the spinal cord during thoracic aortic surgery (Berntman *et al.* 1981). Preliminary studies have also demonstrated that providing convective cooling to a patient's cutaneous layer proves an effective therapy for heat stress (Iaizzo *et al.* 1994).

A device for inducing controlled, mild hypothermia, designated Polar Bair™, has been developed to produce cool convective air which is diffused over a patient by a standard Bair Hugger® blanket. Thermoelectric technology is utilized to cool the air. This technology offers several inherent advantages compared with conventional cooling systems such as reliability, quiet operation, and precision temperature control. Furthermore, a thermoelectric cooler can become a heater by merely reversing voltage polarity. One- and three-dimensional mathematical models were developed to quantify the performance characteristics of a three-stage cooling unit. System optimization studies were conducted both numerically and experimentally to assess machine capabilities.

METHODS

Design methodology for the multistage cooling system included a numerical analysis of the fin arrays which extract heat from the air and those which deliver heat to a sink. The heat exchange system consists of a stacked arrangement of three stages, each composed of a central air-cooling fin array, two flanking heat-sink arrays, and eight thermoelectric heat pump modules, as illustrated in Figure 1. The air-cooling arrays are aligned in series to provide a continuous airflow passage, while the heat-sink arrays are arranged in parallel. Each airflow circuit is provided with its own blower, and the cool side is fitted with a 0.2-micron HEPA air filter. The three air-cooling arrays are constructed of 1.02-mm thick, 1100 series aluminum fins staked between 7.94-mm-thick aluminum baseplates (surfaces lapped), while each of the six heat-sink arrays, constructed of the same materials, has one baseplate. Four thermoelectric modules (24 total) are installed between each cold and hot baseplate. A 900-W DC power supply developed at Augustine Medical, Inc. is required to power the modules. The respective convective heat flows from the cool-side air and to the heat-sink air are coupled via heat conduction across the thermoelectric modules.

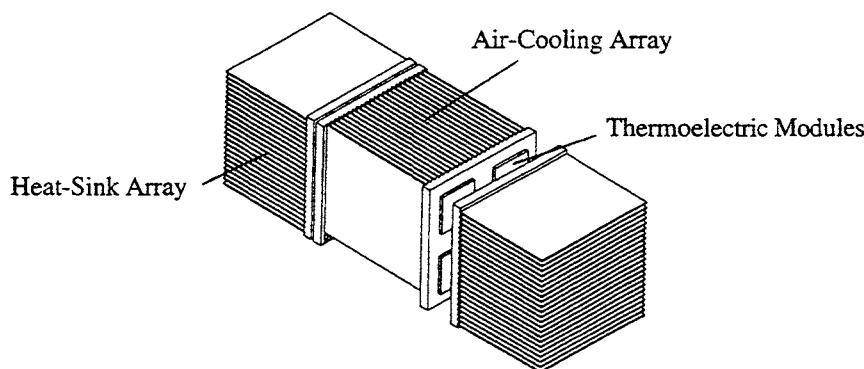


Figure 1. Single Air-Cooling and Heat-Sink Stage

An effective one-dimensional mathematical model was developed to quantify performance of the cooling-unit fin arrays. This accurate, uncomplicated model characterizes the fin array effectiveness in terms of the temperature reduction ratio (TRR) and the pressure drop associated with each fin assemblage. The TRR indicates the degree to which a given fin array reduces the incoming air temperature relative to the maximum possible air temperature reduction (i.e., when the air attains the thermoelectric module cold-face temperature). The per-stage TRR is calculated for an ideal flow channel whose wall surface temperature remains constant. Realistically, channel walls exhibit nonuniform temperatures along both the longitudinal and transverse axes. An iteration

scheme utilizing fin array thermal resistance readily eliminates heat flow imbalances associated with the temperature nonuniformities. The Nusselt number, used to calculate heat transfer coefficients and TRR, is based upon previously available analytical results (Sparrow 1992). Per-stage pressure drop is equivalent to the individual channel pressure drops (Kays *et al.* 1972).

The one-dimensional program calculates the TRR and pressure drops by varying geometrical and operating parameters. These include a prescribed set of channel and fin dimensions and the volumetric airflow rate. For a multistage device, the overall system temperature reduction ratio is determined from the per-stage TRR and the number of stages in the cooling device. The total pressure drop is subsequently calculated by summing the pressure drops from the individual stages. Numerically generated values of the system temperature reduction ratio and pressure drop, along with knowledge of non-thermal design constraints such as fabrication geometry and weight limitations, enable the engineer to optimize the heat exchange system.

A three-dimensional, finite-difference program (FLUENT) was employed on the Cray X-MP at the Minnesota Supercomputer Institute to verify the 1-D model results. Upon noting symmetry conditions, the channel velocity distribution was solved for a particular geometry and airflow rate. The temperature distribution was then solved with appropriate wall boundary conditions. A mesh size of 15x10x10 was selected for the analysis, and post-processing of the data yielded heat transfer coefficients comparable with the 1-D model results.

Experiments have been performed to determine the heat transfer characteristics for both the individual fin arrays and the completed prototype device. These included: 1) determination of heat-sink fin array performance as a function of fin length and airflow hydrodynamic development, 2) system pressure drop characteristics, 3) air temperature drop as a function of airflow rate and total thermoelectric module input power, and 4) suppression of extraneous heat uptake in the final design, e.g., heat uptake through the Bair Hugger® blanket supply hose.

RESULTS

Conventional 1-D heat transfer theory, substantiated by a rigorous 3-D numerical simulation, has provided results that relate the cooling efficiency of the system to the cold-side airflow rate and the heat exchanger geometry. Experiments conducted with the prototype machine have attained cooled air approximately 17°C below ambient at a flow rate of 850 L/min. More judicious insulation utilization in the final product has decreased heat uptake in the cooled air downstream of the heat exchanger. For example, another 1.1°C of temperature reduction can be realized by insulating the cooled-air delivery hose connecting the heat exchanger and the diffusing blanket with Thinsulate®. Exhaust heat has been wisely utilized to both cool the power supply and to evaporate all condensate. A sophisticated, microprocessor-driven control system operates the unit at three cooling and warming temperature settings within $\pm 1.5^\circ\text{C}$.

CONCLUSIONS

A prototype thermoelectric device has been designed and constructed that can effectively serve as a means for providing cooled, convective air for therapeutic purposes. The design was facilitated by the use of computer-based simulations of the convective and conductive heat transfer processes. Thermoelectric systems offer several inherent advantages such as longevity, compactness, and quiet operation. Another major advantage of the thermoelectric device is that by merely reversing polarity, heated convective air can be produced. This dual-purpose capability would be extremely beneficial in an OR or ICU environment where space and cost limitations may exist.

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