

Thermal Management of Vehicular Payloads Using Nanofluid Augmented Coolant Rail - Modeling and Analysis

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ABSTRACT

Various payloads, such as electronic systems, have become an integral part of modern military ground vehicles. These payloads often feature high thermal density that need to be effectively managed, especially under demanding operating conditions, to maintain system reliability. This paper describes the modeling and analysis of a nanofluid augmented coolant rail combined with thermoelectric devices to address the cooling challenges posed by these payloads. A sensitivity analysis has been performed to investigate the nanoparticle enhancement model. Numerical results obtained show that the convective heat transfer coefficient can be enhanced by up to 16% with the augmentation of nanoparticles into the base fluid. The results also show that the peak computer temperature is rather insensitive to the complexity of the model used and that the proposed system provides cooling performance which would not be possible with traditional air-cooled heat sinks.

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INTRODUCTION

Modern military ground vehicles, such as Force Protection's Cougar MPAV, may carry a vast array of electronic equipment to perform command and control tasks that require reliable temperature control to maintain system integrity. Computational technology continues to improve, allowing progressively smaller package sizes for a given power density in this equipment, raising the heat load on the overall system. Particularly in military applications, electronic systems may be operated in a wide range of conditions, including hot desert climates where heat rejection is difficult because of the decreased differential between the ambient conditions and the equipment's maximum operating temperature. To ensure adequate cooling in adverse ambient conditions, including desert environments, a cooling system must be developed which is capable of cooling the electronics to or below ambient temperatures while maintaining the packaging flexibility necessary for these components.

Additionally, such a system must be robust enough for reliable operation in combat environments.

Thermal management technology for automotive applications has been developed to use electronic control for precise temperature control. The liquid cooling systems involved lend themselves well to heat transfer in electronic equipment and are in fact currently being used in several server and after-market computational systems [1]. Electrically powered cooling components may be computer controlled to maintain prescribed temperatures and reduce power consumption [2]. Recent developments, and accompanying mathematical models, in heat exchanger design allow greatly increased convective heat transfer coefficients with insight into their operation [3,4]. The primary limitation, however, of standalone liquid cooling remains the required temperature differential over the ambient conditions which may result in unacceptable device temperatures in hot climates.

Peltier effect thermoelectric coolers (TEC) have demonstrated attractive cooling properties for computational applications (i.e. capacitors, processors) since they can cool these system components below ambient temperatures in certain operating regimes [5]. The heat transfer process occurs without moving parts in the TEC module, thus providing a distinct advantage over conventional vapor compression cycles. The cooling effect in Peltier devices is achieved by a current flow through the junction of two dissimilar materials. The cooling available from TEC's has enabled processor overclocking capabilities in certain applications [6]. Additionally, large TEC's may serve multiple computer chips, such as in multi-core processing, as demonstrated by [7]. However, an effective means must exist to reject heat to the TEC module's thermal conductivity and overcome the generated heat flux.

The heat rejection accommodations of the cooling system are critical to the successful operation of the TEC system, due to the inefficiency of TEC modules. A high capacity cold reservoir is required to achieve such heat rejection, though this goal is not a significant design issue when space requirements are not imposed, and passive cooling systems such as free convection may be implemented to meet the enhanced cooling demands [8]. More conventional installations, such as the ones demonstrated by [9], use forced convection and have proven to yield adequate performance. Space limitations, however, demand the implementation of different technologies, and new electronic systems may feature such high power densities that direct air cooling is unable to meet the heat rejection demands. Liquid cooling has proven capable of meeting these demands and is well suited to thermoelectric systems [10].

Also, experiments have shown that, by adding nanoparticles with much higher thermal conductivity than the base fluid, the thermal transfer properties of the base fluid are enhanced [11], [12], [13], [14], [15], [16], [17]. This enhancement is attractive for use in thermal management systems by providing increased thermal protection for mission critical components. However, the mechanisms of this enhancement are still debated due to the inconsistencies present in the available experimental data and the widely varying models that have been developed [12] [13], [15], [17]. Therefore, precise mathematical modeling of nanofluids remains a debated and uncertain area of research. Due to this uncertainty, it is highly desirable to compare the influence of multiple nanofluid models in simulations in order to study their significance in modeling accuracy to achieve better computational times and to achieve better computational stability.

The development of an integrated liquid and TEC cooling system with nanofluid particles should offer greater packaging design flexibility and modular designs for small electronics. This approach should be well suited to military and avionics applications where space limitations and high ambient temperatures make cooling difficult. The implementation of multiple cooling loops so that the

thermoelectrics are not in direct contact with their respective electronic heat loads eliminates condensation problems and minimizes the cooling footprint on the actual electronic component. Nanofluids will enhance the cooling performance and reduce the thermal resistance of the multiple loop system. Also, investigation of nanofluid modeling techniques will provide insight into the effectiveness of various models and demonstrate the effectiveness of the proposed cooling system. The remainder of the paper has been organized as follows. Section 2 presents the fundamental concepts of the modeling of nanofluids and thermoelectrics. A thermal system model is introduced in Section 3 for an electronic system featuring computer chips and cooling components used for various case studies. Representative numerical results will be provided and discussed in Section 4. Finally, the summary is contained in Section 5.

FUNDAMENTALS OF NANOFLUIDS AND THERMOELECTRICS

The issue of cooling electronic payloads has been approached by modeling a system containing combined thermoelectric and nanofluid technologies to allow for maximum thermal protection and packaging flexibility. Critical issues of modeling the properties of nanofluids have been discussed. Also, conventional thermoelectric formulations have been implemented for modeling.

Nanofluids

Nanofluids have been a source of research for the past several years due to their observed ability to enhance the thermal transfer properties of base fluid properties [11], [12], [13], [16], [18]. Micron sized particles were originally used in research for enhancing the heat transfer properties of cooling fluids; however, these particles were deemed impractical for many applications because the resultant fluid required large increases in pumping power and also increased the pipe wall friction leading to increased pipe wear [11]. However, as research progressed, nano-sized particles were introduced into these systems and demonstrated attractiveness in the enhancement of thermal transfer characteristics while greatly reducing the negative aspects of pumping power and pipe wear, making nanofluids a much more viable option to use in practical thermal protection systems [11].

While these enhancements have been well documented, the mechanisms that cause these enhancements are still greatly debated [11], [12], [13], [16], [17], [18]. As revealed from these references, inconsistencies in the experimental data as well as the wide range of models available regarding nanoparticle enhancement of base fluids remain the primary causes of this ongoing debate. While this enhancement has been shown to depend on the shape, size, and concentration of the nanoparticles, the underlying mechanisms of this enhancement have yet to be conclusively decided. Among many models that have been used in the past, the more prominent models include classic models such as Maxwell's

equation for thermal conductivity and Einstein's model for viscosity [18], [19], Brownian motion [20], [21], or simply the utilization of curve fitting of data [16]. The importance of the latter two models is shown by the strong temperature dependence that these enhancements demonstrate [16], [19]. These facts, along with the inconsistencies in the data, cause difficulties in modeling the effects that nanoparticles have on the thermal transfer properties of their base fluids, which leave the modeling of nanofluids an unresolved area of research.

Another difficulty in modeling the enhancement of the overall convective heat transfer coefficient, h , is the fact that, while there have been many studies to observe the enhancement of the thermal conductivity of base fluids by the addition of nanoparticles, very few studies have been performed in the area of the increase of the viscosity of base fluids by the addition of nanoparticles [12], [13], [16], [19], [22]. However, in the study of convective heat transfer, it is very important to study not only the enhancement of thermal conductivity but also the increase of viscosity since both properties affect the convective heat transfer coefficient. While analyses on the combined effects of the enhancements of thermal conductivity and viscosity have been performed in a few systems, these combined effects of these enhancements need to be established for each proposed thermal management system.

With the debate still ongoing and the above challenges in mind, one practical concern with the modeling of nanofluids is how the different proposed models available affect the final outcome of the simulation being utilized. As mentioned previously, the models available to describe these thermal transfer enhancements range from the simple classic models to very complicated models that include Brownian motion effects and experimental curve fitting. Therefore, determining the sensitivity of the final result on the nanofluid model would provide much insight into the ability to save computational time and increase the stability of the computational model. Therefore, it is a goal of this paper to establish the sensitivity of the nanofluid model used to the final result of the model described later in this paper.

Thermoelectrics

The heat transfer behavior of a Peltier effect device, illustrated in Figure 1, is regulated by the flow of current, i , through the unit. The current flow is dependent on both the unit's electrical properties and the temperature of the hot and cold sides of the unit. Thus the relationship for current dependent upon supply voltage, V , electrical resistance, R_{TEC} , and the temperatures of the two plates, T_H and T_C , may be stated as

$$i = \frac{1}{R_{TEC}} V - \alpha(T_H + T_C) \cong \frac{1}{R_{TEC}} V \quad (1)$$

where the parameter α denotes the Seibec coefficient of the thermoelectric material (note that α is negative) [23]. Since α

is small, its effect may be neglected so that the consumed power, P , becomes

$$P = i^2 R_{TEC} + \alpha i (T_H + T_C) \cong i^2 R_{TEC} \quad (2)$$

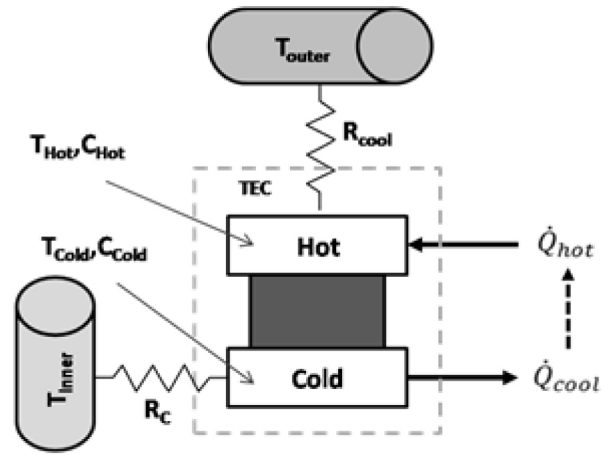


Figure 1. Schematic of thermoelectric concept

The heat removal equation for the cold side of the TEC can be described based on electrical resistance, Peltier effect, and thermal conductivity so that the heat removed, $\dot{Q}_{cold}$, is given by [24]

$$\dot{Q}_{cold} = 2n(\alpha i T_{avg}) - \frac{1}{2} i^2 R_{TEC} - A_{TEC} k_{TEC} (T_H - T_C) \quad (3)$$

where $T_{avg} = (1/2)(T_H + T_C)$ is in K, and n is the number of thermoelectric couples in the TEC. Now, α may not be neglected from this equation in the Peltier term because n is sufficiently large. Using Ohm's law, the heat transfer behavior may then be stated in terms of the supply voltage so that Equation (3) is restated as

$$\dot{Q}_{cold} = 2n(\alpha T_{avg}) \frac{V}{R_{TEC}} - \frac{1}{2} \frac{V^2}{R_{TEC}} - A_{TEC} k_{TEC} (T_H - T_C) \quad (4)$$

In this system the thermal conductivity influences both sides, and the resistance heat is shared, so the heat added to the hot side may be given as

$$\dot{Q}_{hot} = -2n(\alpha T_{avg}) \frac{V}{R_{TEC}} + \frac{1}{2} \frac{V^2}{R_{TEC}} + A_{TEC} k_{TEC} (T_H - T_C) \quad (5)$$

The TEC's efficiency may be described by a figure of merit, $Z = \alpha^2 / (k_{TEC} R)$ whose magnitude demonstrates the limitations of thermoelectric systems. In fact, for most thermoelectric systems, $ZT_{avg} \leq 1$ [25].

A power-saving strategy has also been implemented on the thermoelectric system model so that the units will only be