Energy 39 (2012) 236-245

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Design of heat sink for improving the performance of thermoelectric generator using two-stage optimization

Chien-Chang Wang^a, Chen-I Hung^{a,**}, Wei-Hsin Chen^{b,*}

^a Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC ^b Department of Greenergy, National University of Tainan, Tainan 700, Taiwan, ROC

ARTICLE INFO

Article history: Received 16 October 2011 Received in revised form 6 January 2012 Accepted 13 January 2012 Available online 16 February 2012

Keywords: Thermoelectric generator (TEG) Heat sink design Two-stage optimization Compromise programming Scaling effect Finite element scheme

ABSTRACT

Thermoelectric (TE) devices can provide clean energy conversion and are environmentally friendly; however, little research has been published on the optimal design of air-cooling systems for thermoelectric generators (TEGs). The present study investigates the performance of a TEG combined with an air-cooling system designed using two-stage optimization. An analytical method is used to model the heat transfer of the heat sink and a numerical method with a finite element scheme is employed to predict the performance of the TEG. In the first-stage optimization, the optimal fin spacing for a given heat sink geometry is obtained in accordance with the analytical method. In the second-stage optimization, called compromise programming, decreasing the length of the heat sink by increasing its frontal area ($W_{HS}H_f$) is the recommended design approach. Using the obtained compromise point, though the heat sink efficiency is reduced by 20.93% compared to that without the optimal design, the TEG output power density is increased by 88.70%. It is thus recommended for the design of the heat sink. Moreover, the TEG power density can be further improved by scaling-down the TEG when the heat sink length is below 14.5 mm.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Over the last several decades, there has been a dramatic progress in the development of green energy technology which can reduce greenhouse gas emissions and fossil fuel usage. Thermoelectric (TE) devices, which consist of p-type and n-type semiconductors, can be considered as a useful tool to practice the green energy technology. TE devices can be divided into two types, namely thermoelectric coolers (TECs) [1–4] and thermoelectric generators (TEGs) [5–8]. TECs convert electricity into thermal energy for cooling via the Peltier effect, whereas, TEGs convert thermal energy, say, waste heat, into electrical power via the Seebeck effect.

Unlike convectional heat engines or compression refrigerators, TE devices are solid-state; they contain neither moving parts nor refrigerants [9]. Therefore, the whole system can be simplified and operated over an extended period of time without maintenance [10]. TE devices can produce energy without using fossil fuel and can thus reduce greenhouse gas emissions. However, the energy conversion efficiency of TE devices is lower than those of convectional heat engines or refrigerators [11]. The efficiency of TEGs and the coefficient of performance (COP) of TECs are functions of not only the figure of merit (ZT) but also the temperature difference across the devices [12]. ZT is the performance index of a thermoelectric material. Its value is relatively low (about 1.0) for the best existing commercial TE cooling modules whereas that for conventional air-conditioning system is about 4.0 [13]. Consequently, a strategy for improving the performance of TE devices is needed.

In reviewing past research concerning thermal design of TEGs, a number of studies have been reported. For example, Esarte et al. [14] employed a theoretical method to analyze the influence of the design parameters of heat exchangers on the power supplied by a TEG. The theoretical results well matched the experimental values for low flow rates but not for high flow rates. Chen et al. [15] found that heat transfer irreversibility affected the performance of TEG and thus had to be considered in analysis. A TEG system combined with the heat exchangers at both the hot and cold side was numerically modeled by Astrain et al. [16]. Their results showed that when the thermal resistances of heat exchangers on both sides of the TEG were decreased by 10%, the TEG output power was increased by 8%.

Recently, waste heat has been recovered for further usage. Waste heat can be used for space and water heating [17,18],





^{*} Corresponding author. Tel.: +886 6 2605031; fax: +886 6 2602205.

^{**} Corresponding author. Tel.: +886 6 2757575x62169; fax: +886 6 2352973. *E-mail addresses*: cihung@mail.ncku.edu.tw (C.-I. Hung), weihsinchen@ gmail.com (W.-H. Chen).

^{0360-5442/\$ –} see front matter @ 2012 Elsevier Ltd. All rights reserved. doi:10.1016/j.energy.2012.01.025

2	2	-
2	3	1

$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Nomenclature		T_{∞}	Fluid inlet temperature (K)		
A_c Cross-sectional area (mm ²) V Total volume of heat sink (mm ³) A Surface area (mm ²) W Width (mm) C_p Specific heat at constant pressure (kJ kg ⁻¹ K ⁻¹) X Geometry parameter of the heat sink (mm) D_T Depth of TE element (mm) (x,y) Real point in the compromise programming D_Z Fin-to-fin spacing (mm) (x,y) Real point in the compromise programming G Ratio of the cross-sectional area to length of TE element (mm) $Greek$ letters G Ratio of the cross-sectional area to length of TE element (mm) $Greek$ letters H_f Fin height (mm) φ Electric scalar potential (V) h Average heat transfer coefficient of the fins (W m ⁻² K ⁻¹) φ Electric scalar potential (V) h Heat transfer coefficient (W m ⁻² K ⁻¹) φ Fluid thermal diffusivity (m ² s ⁻¹) f Electric current (A) φ Fluid viscosity (N s m ⁻²) f Electric current density vector (A m ⁻²) ρ Fluid density (kg m ⁻³) f Number of finsSubscripts N_{TE} Number of TEG (mW) B Heat sink base P Output power of TEG (mW) B Heat sink f Pressure drop across the heat sink (N m ⁻²) F f Fin perimeter (mm) f F f Heat generation per unit volume (W m ⁻³) HS f Heat generation per unit volume (W m ⁻³) F f Heat fransfer rate for the boundary layer flow limit (t _f	Fin thickness (mm)	
$\begin{array}{llllllllllllllllllllllllllllllllllll$		A_c	Cross-sectional area (mm ²)	Ň	Total volume of heat sink (mm ³)	
$\begin{array}{llllllllllllllllllllllllllllllllllll$		Α	Surface area (mm ²)	W	Width (mm)	
$ \begin{array}{cccc} D_{\mathrm{TE}} & \mathrm{Depth} \ \mathrm{of} \ \mathrm{TE} \ \mathrm{element} \ (\mathrm{mm}) & (x,y) & \mathrm{Real point} \ \mathrm{in} \ \mathrm{the compromise programming} \\ D_{\mathrm{g}} & \mathrm{Fin-to-fin} \ \mathrm{spacing} \ (\mathrm{mm}) & (x^*y)^* & \mathrm{Ideal point} \ \mathrm{in} \ \mathrm{the compromise programming} \\ \overline{F} & \mathrm{Electric} \ \mathrm{fid} \ \mathrm{intensity vector} \ (\mathrm{V} \ \mathrm{m}^{-1}) & ZT & \mathrm{Dimensionless} \ \mathrm{TE} \ \mathrm{figure} \ \mathrm{of} \ \mathrm{mm} \ \mathrm{figure} \ $		C_p	Specific heat at constant pressure (kJ kg ⁻¹ K ⁻¹)	Χ	Geometry parameter of the heat sink (mm)	
$ \begin{array}{cccc} D_{\rm g} & {\rm Fin-to-fin spacing (mm)} & (x^*,y^*) & {\rm Ideal point in the compromise programming} \\ E & {\rm Electric field intensity vector (V m^{-1})} & ZT & {\rm Dimensionless TE figure of merit} \\ \hline \\ T & {\rm Distance function in the compromise programming} \\ G & {\rm Ratio of the cross-sectional area to length of TE} & element (mm) & & & & \\ element (mm) & & & & & \\ R & {\rm Average heat transfer coefficient of the fins (W m^{-2} K^{-1})} & & & \\ P & {\rm Fin height (mm)} & & & & \\ P & {\rm Electric current (A)} & & & & \\ P & {\rm Electric current (A)} & & & & \\ P & {\rm Electric current density vector (A m^{-2})} & & & \\ P & {\rm Fluid viscosity (M s m^{-2})} & & \\ P & {\rm Fluid density (kg m^{-3})} & \\ R & {\rm Thermal conductivity (W m^{-1} K^{-1})} & & \\ P & {\rm Cutput power of fins} & & \\ Subscripts & \\ N_{\rm TE} & {\rm Number of TEG couple} & B & {\rm Heat sink base} & \\ P & {\rm Output power of TEG (mW)} & B & {\rm Heat sink base} & \\ P & {\rm Output power density of TEG, } = P/A_{C,{\rm TE}} (mW mm^{-2}) & F & {\rm Fluid} & \\ P & {\rm Prissure drop across the heat sink (N m^{-2})} & F & {\rm Fluid} & \\ P & {\rm Pradd number, } = r/\alpha & f & {\rm Fin} & \\ \frac{1}{q} & {\rm Heat generation per unit volume (W m^{-3})} & {\rm HS} & {\rm Heat sink} & \\ \frac{1}{q} & {\rm Heat transfer rate (M)} & {\rm L} & {\rm External load} & \\ Q_{I} & {\rm Heat transfer rate for the fould veloped flow limit m} & \\ Q_{S} & {\rm Heat transfer rate for the fully developed flow limit m} & \\ (W) & {\rm n} & {\rm n-type for TE element} & \\ R & {\rm Electric resistance (\Omega)} & {\rm opt} & {\rm Optimum} & \\ S & {\rm Seebeck coefficient (V K^{-1})} & p & {\rm put power of TE element} & \\ T & {\rm Absolute temperature (K)} & {\rm TE} & {\rm Thermoleclerric element} & \\ T & {\rm Absolute temperature (K)} & {\rm TE} & {\rm Thermoleclerric element} & \\ T & {\rm Absolute temperature of the fins (K)} & {\rm TE} & {\rm Thermoleclerric element} & \\ T & {\rm Total heat sink heat transfer area} & \\ \end{array}$		\dot{D}_{TE}	Depth of TE element (mm)	(x,y)	Real point in the compromise programming	
\vec{E} Electric field intensity vector (V m ⁻¹) ZT Dimensionless TE figure of merit f Distance function in the compromise programming G Ratio of the cross-sectional area to length of TE element (mm) G $Greek letters$ α H_f Fin height (mm) φ Electric scalar potential (V) h Average heat transfer coefficient of the fins (W m ⁻² K ⁻¹) φ Electric scalar potential (V) h Heat transfer coefficient (W m ⁻² K ⁻¹) φ Fluid viscosity (N s m ⁻²) I_{-} Electric current (A) ν Fluid density (kg m ⁻³) K Thermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electrical resistivity (Ω m) L Length (mm) $Subscripts$ N_{TE} Number of finsSubscripts N_{TE} Number of TEG (mW) B Heat sink base P' Output power density of TEG, $=P/A_{c,TE}$ (mW mm ⁻²) F Fluid P_f Fin perimeter (mm) eff Effective Δp Pressure drop across the heat sink (N m ⁻²) F Fluid P_f Pressure drop across the heat sink (N m ⁻²) F Fluid q Heat transfer rate for the boundary layer flow limit (W)IoseHeat sink Q_i Heat transfer rate for the fully developed flow limit (W)IoseHeat loss from the side surfaces of the TE element Q_i Heat transfer rate for the fully developed flow limit (W)IoseHeat loss from the side surfaces of the TE element Q_i Heat transfer rate for the fully developed flow limit		D_{g}	Fin-to-fin spacing (mm)	(x^{*}, y^{*})	Ideal point in the compromise programming	
fDistance function in the compromise programming Ratio of the cross-sectional area to length of TE element (mm)Greek letters a aFiluid thermal diffusivity (m² s ⁻¹) aHfFin height (mm) α Filuid thermal diffusivity (m² s ⁻¹) η Efficiency (%)hHeat transfer coefficient of the fins (W m ⁻² K ⁻¹) μ Ffluid thermal diffusivity (m² s ⁻¹)IElectric current (A) ν Fluid thermal diffusivity (m² s ⁻¹)JElectric current density vector (A m ⁻²) ρ Fluid kinematic viscosity (N s m ⁻²)JElectric current density vector (A m ⁻²) ρ Fluid density (kg m ⁻³)kThermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electrical resistivity (Ω m)LLength (mm)SubscriptsNreNumber of finsSubscriptsNreNumber of TEG coupleBHeat sink basePOutput power of TEG (mW)baseBasePOutput power of TEG, $= P/A_{c,TE}$ (mW mm ⁻²)FFluidApPressure drop across the heat sink (N m ⁻²)FFluidPPradut number, $= n/\alpha$ fF q Heat generation per unit volume (W m ⁻³)HSHeat sinkqHeat transfer rate for the boundary layer flow limit (W)lossHeat sink conficient for the side surfaces of the TE elementQHeat transfer rate for the fully developed flow limit (W)mnn-type for TE elementQHeat transfer rate for the fully developed flow limit (W)mnn-type fo		Ē	Electric field intensity vector (V m^{-1})	ZT	Dimensionless TE figure of merit	
GRatio of the cross-sectional area to length of TE element (mm)Greek letters aFilidi thermal diffusivity (m² s ⁻¹) H_f Fin height (mm) φ Electric scalar potential (V) h Average heat transfer coefficient of the fins (W m ⁻² K ⁻¹) φ Electric scalar potential (V) h Heat transfer coefficient (W m ⁻² K ⁻¹) μ Fluid viscosity (M s m ⁻²) I_{-} Electric current (A) ν Fluid density (Vs m ⁻²) J Electric current density vector (A m ⁻²) ρ Fluid density (Vg m ⁻³) k Thermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electric aresistivity (Ω m) L Length (mm)Subscripts N_{f} Number of finsSubscripts N_{TE} Number of TEG couple B Heat sink base P' Output power density of TEG, $=P/A_{c,TE}$ (mW mm ⁻²) c Cold side of TE element P_f Fin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m ⁻²) F Fluid q Heat generation per unit volume (W m ⁻³)HSHeat sink q Heat generation per unit volume (W m ⁻³)HSHeat loss from the side surfaces of the TE element q Heat transfer rate for the fully developed flow limit (W)IsKatimum q Heat transfer rate for the fully developed flow limit (W)Is q Heat transfer rate for the fully developed flow limit (W)IsNatimum q Heat transfer rate for the fully developed flow limit (W) <t< th=""><th></th><th>f</th><th>Distance function in the compromise programming</th><th></th><th>-</th></t<>		f	Distance function in the compromise programming		-	
element (mm) α Fluid thermal diffusivity (m ² s ⁻¹) H_f Fin height (mm) φ Electric scalar potential (V) h Average heat transfer coefficient of the fins (W m ⁻² K ⁻¹) μ Ellectric scalar potential (V) h Heat transfer coefficient (W m ⁻² K ⁻¹) μ Fluid viscosity (N s m ⁻²) I_{-} Electric current (A) ν Fluid kinematic viscosity (m ² s ⁻¹) J Electric current density vector (A m ⁻²) ρ Fluid density (kg m ⁻³) k Thermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electrical resistivity (Ω m) L Length (mm) N_T Number of fins $Subscripts$ N_T Number of TEG couple B Heat sink base P Output power of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²) c Cold side of TE element P_f Fin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m ⁻²) F Fluid P_r Prandtl number, $\equiv \nu/\alpha$ f Fin q Heat generation per unit volume (W m ⁻³)HSHeat sink q Heat transfer rate (W) L External load Q_L Heat transfer rate for the boundary layer flow limit (W)nn Q_s Heat transfer rate for the fully developed flow limitnn-type for TE element Q_s Heat transfer rate (Ω) ρ Puppe for TE element Q_s Heat transfer rate (Ω) ρ Puppe for TE element Q_s Heat transfer rate for the fully develo		G	Ratio of the cross-sectional area to length of TE	Greek le	Greek letters	
H_f Fin height (mm) φ Electric scalar potential (V) h Average heat transfer coefficient of the fins (W m ⁻² K ⁻¹) η Efficiency (%) h Heat transfer coefficient (W m ⁻² K ⁻¹) μ Fluid viscosity (N s m ⁻²) I_{-} Electric current (A) ν Fluid kinematic viscosity (m ² s ⁻¹) J Electric current density vector (A m ⁻²) ρ Fluid density (kg m ⁻³) k Thermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electrical resistivity (Ω m) L Length (mm) ρ_e Electrical resistivity (Ω m) K Number of finsSubscriptsNreeNumber of TEG couple B Heat sink base P Output power of TEG (mW)baseBaseBase case P' Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²) c Cold side of TE element P_f Fin perimeter (mm)effEfficitive Δp Pressure drop across the heat sink (N m ⁻²) F Fluid P Prandtl number, $\equiv \nu/\alpha$ f Fin q Heat generation per unit volume (W m ⁻³)HSHeat sink q Heat transfer rate (W)LExternal load Q Heat transfer rate for the boundary layer flow limit (W)IossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limit n n-type for TE element Q_s Heat transfer rate for the fully developed flow limit n n-type for TE element Q_s <th></th> <th></th> <th>element (mm)</th> <th>α</th> <th>Fluid thermal diffusivity $(m^2 s^{-1})$</th>			element (mm)	α	Fluid thermal diffusivity $(m^2 s^{-1})$	
\vec{h} Average heat transfer coefficient of the fins (W m ⁻² K ⁻¹) η Efficiency (%)hHeat transfer coefficient (W m ⁻² K ⁻¹) μ Fluid viscosity (N s m ⁻²)IElectric current (A) ν Fluid kinematic viscosity (m ² s ⁻¹)JElectric current density vector (A m ⁻²) ρ Fluid kinematic viscosity (Ω m)kThermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electrical resistivity (Ω m)LLength (mm) ρ_e Electrical resistivity (Ω m)KNumber of finsSubscriptsNreNumber of TEG coupleBHeat sink basePOutput power of TEG (mW)baseBase caseP''Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²)cCold side of TE elementP _f Fin perimeter (mm)effEffectiveΔpPressure drop across the heat sink (N m ⁻²)FF luidPrPrandt number, $\equiv \nu/\alpha$ fFin \vec{q} Heat generation per unit volume (W m ⁻³)HSHeat sink \vec{q} Heat transfer rate (W)LExternal loadQHeat transfer rate for the boundary layer flow limit (W)lossHeat sinf set surfaces of the TE elementQsHeat transfer rate (V K ⁻¹)pp-type for TE elementQsSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric elementTAbsolute temperature of the fins (K)tTotal heat sink heat transfer area		H_{f}	Fin height (mm)	φ	Electric scalar potential (V)	
hHeat transfer coefficient (W m ⁻² K ⁻¹) μ Fluid viscosity (N s m ⁻²)IElectric current (A) ν Fluid kinematic viscosity (m ² s ⁻¹)JElectric current density vector (A m ⁻²) ρ Fluid density (kg m ⁻³)kThermal conductivity (W m ⁻¹ K ⁻¹) ρ Electrical resistivity (Ω m)LLength (mm) P_{e} Electrical resistivity (Ω m)NfNumber of finsSubscriptsNTENumber of TEG coupleBHeat sink basePOutput power of TEG (mW)baseBase caseP''Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²)cCold side of TE element Δp Pressure drop across the heat sink (N m ⁻²)FFluidPrPrandtl number, $\equiv \nu/\alpha$ fFin $\frac{q}{q}$ Heat flux vector (W m ⁻²)hHot side of TE elementQHeat flux vector (W m ⁻²)hHot side of TE elementQHeat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE elementQsHeat transfer rate for the fully developed flow limitmnn-type for TE elementQsSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric elementTAbsolute temperature of the fins (K)TEThermoelectric element		ħ	Average heat transfer coefficient of the fins (W $m^{-2} K^{-1}$)	η	Efficiency (%)	
IElectric current (A) ν Fluid kinematic viscosity (m² s ⁻¹)JElectric current density vector (A m²) ρ Fluid density (kg m³)kThermal conductivity (W m¹ K⁻1) ρ_e Electrical resistivity (Ω m)LLength (mm) ρ_e Electrical resistivity (Ω m)LLength (mm) ρ_e Electrical resistivity (Ω m)NTENumber of finsSubscriptsNTENumber of TEG coupleBHeat sink basePOutput power density of TEG, $=P/A_{c,TE}$ (mW mm²)cCold side of TE elementP''Output power density of TEG, $=P/A_{c,TE}$ (mW mm²)FFluidPrPressure drop across the heat sink (N m²)FFluidPrPrandtl number, $=\nu/\alpha$ fFin q Heat generation per unit volume (W m³)HSHeat sink q Heat flux vector (W m²)hHot side of TE elementQHeat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limitmaxMaximum (W) nn-type for TE element Q_s Seebeck coefficient (V K⁻1)pp-type for TE element T_w Surface temperature of the fins (K)TEThermoelectric element		h	Heat transfer coefficient (W $m^{-2} K^{-1}$)	μ	Fluid viscosity (N s m^{-2})	
\vec{J} Electric current density vector (A m ⁻²) ρ Fluid density (kg m ⁻³) k Thermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electrical resistivity (Ω m) L Length (mm) ρ_e Electrical resistivity (Ω m) N_f Number of finsSubscripts N_{TE} Number of TEG couple B Heat sink base P Output power of TEG (mW)baseBase case P'' Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²) c Cold side of TE element P_f Fin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m ⁻²) F Fluid P' Pradtl number, $\equiv \nu/\alpha$ f Fin q Heat generation per unit volume (W m ⁻³)HSHeat sink q Heat flux vector (W m ⁻²) h Hot side of TE element Q Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limitmaxMaximum (W) n n n-type for TE element R Electric resistance (Ω) p p-type for TE element S Seebeck coefficient (V K ⁻¹) p p p-type for TE element T_w Surface temperature of the fins (K) t Total heat sink heat transfer area		I	Electric current (A)	ν	Fluid kinematic viscosity $(m^2 s^{-1})$	
kThermal conductivity (W m ⁻¹ K ⁻¹) ρ_e Electrical resistivity (Ω m)LLength (mm)NfNumber of finsSubscriptsNTENumber of TEG coupleBHeat sink basePOutput power of TEG (mW)baseBase caseP''Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²)cCold side of TE elementP''Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²)FFluidPrPressure drop across the heat sink (N m ⁻²)FFluidPrPrandtl number, $\equiv \nu/\alpha$ fFin \vec{q} Heat generation per unit volume (W m ⁻³)HSHeat sink \vec{q} Heat flux vector (W m ⁻²)hHot side of TE elementQHeat transfer rate (W)LExternal loadQ _I Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE elementQsHeat transfer rate for the fully developed flow limitmaxMaximum(W)nn-rtype for TE elementRElectric resistance (Ω)optOptimumSSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric elementTwSurface temperature of the fins (K)tTotal heat sink heat transfer area		Ī	Electric current density vector (A m^{-2})	ρ	Fluid density (kg m^{-3})	
$ \begin{array}{ccccc} L & \mbox{Length (mm)} & \mbox{Subscripts} \\ \hline N_{TE} & \mbox{Number of fins} & \mbox{Subscripts} \\ \hline N_{TE} & \mbox{Number of TEG couple} & \mbox{B} & \mbox{Heat sink base} \\ \hline P & \mbox{Output power of TEG (mW)} & \mbox{base} & \mbox{Base case} \\ \hline P' & \mbox{Output power density of TEG, $= P/A_{c,TE} (mW mm^{-2}) & c & \mbox{Cold side of TE element} \\ \hline P_{f} & \mbox{Fin perimeter (mm)} & \mbox{eff} & \mbox{Effective} \\ \hline \ P & \mbox{Pressure drop across the heat sink (N m^{-2})} & \mbox{F} & \mbox{Fluid} \\ \hline \ Pr & \mbox{Pradult number, $= \nu/\alpha$} & \mbox{f} & \mbox{Fin} \\ \hline \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \$		k	Thermal conductivity (W $m^{-1} K^{-1}$)	ρ_e	Electrical resistivity (Ω m)	
N_f Number of finsSubscripts N_{TE} Number of TEG couple B Heat sink base P Output power of TEG (mW)baseBase case P'' Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²) c Cold side of TE element P_f Fin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m ⁻²) F Fluid Pr Prandtl number, $\equiv \nu/\alpha$ f Fin \dot{q} Heat generation per unit volume (W m ⁻³)HSHeat sink \dot{q} Heat flux vector (W m ⁻²) h Hot side of TE element Q Heat transfer rate (W) L External load Q_t Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limit m n n -type for TE element R Electric resistance (Ω)optOptimum S Seebeck coefficient (V K ⁻¹) T Absolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K) t Total heat sink heat transfer area		L	Length (mm)			
\dot{N}_{TE} Number of TEG couple B Heat sink base P Output power of TEG (mW)baseBase case P'' Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²) c Cold side of TE element P_f Fin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m ⁻²) F Fluid Pr Prandtl number, $\equiv \nu/\alpha$ f Fin \dot{q} Heat generation per unit volume (W m ⁻³)HSHeat sink q Heat flux vector (W m ⁻²) h Hot side of TE element Q Heat transfer rate (W) L External load Q_I Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limit (W) n n n -type for TE element R Electric resistance (Ω)optOptimum S Seebeck coefficient (V K ⁻¹) T Absolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K)tTotal heat sink heat transfer area		N_f	Number of fins	Subscrip	Subscripts	
POutput power of TEG (mW)baseBase caseP''Output power density of TEG, $\equiv P/A_{C,TE}$ (mW mm ⁻²)cCold side of TE elementP_fFin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m ⁻²)FFluidPrPrandtl number, $\equiv \nu/\alpha$ fFin \dot{q} Heat generation per unit volume (W m ⁻³)HSHeat sink q Heat flux vector (W m ⁻²)hHot side of TE elementQHeat transfer rate (W)LExternal loadQ_IHeat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE elementQ_sHeat transfer rate for the fully developed flow limit (W)nn-type for TE elementQ_sElectric resistance (\Omega)optOptimumSSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric elementT_wSurface temperature of the fins (K)tTotal heat sink heat transfer area		N _{TE}	Number of TEG couple	В	Heat sink base	
P'' Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm $^{-2}$) c Cold side of TE element P_f Fin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m $^{-2}$) F Fluid Pr Prandtl number, $\equiv v/\alpha$ f Fin \dot{q} Heat generation per unit volume (W m $^{-3}$)HSHeat sink q Heat flux vector (W m $^{-2}$) h Hot side of TE element Q Heat transfer rate (W) L External load Q_l Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limit (W) m n n -type for TE element R Electric resistance (Ω)optOptimum S Seebeck coefficient (V K $^{-1}$) F Absolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K) t Total heat sink heat transfer area		Р	Output power of TEG (mW)	base	Base case	
P_f Fin perimeter (mm)effEffective Δp Pressure drop across the heat sink (N m ⁻²) F Fluid Pr Prandtl number, $\equiv \nu/\alpha$ f Fin \dot{q} Heat generation per unit volume (W m ⁻³)HSHeat sink \dot{q} Heat flux vector (W m ⁻²) h Hot side of TE element Q Heat transfer rate (W) L External load Q_i Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limitmaxMaximum (W) n n-type for TE element R Electric resistance (Ω)optOptimum S Seebeck coefficient (V K ⁻¹) p p-type for TE element T Absolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K)tTotal heat sink heat transfer area		P''	Output power density of TEG, $\equiv P/A_{c,TE}$ (mW mm ⁻²)	С	Cold side of TE element	
$\begin{array}{llllllllllllllllllllllllllllllllllll$		P_f	Fin perimeter (mm)	eff	Effective	
PrPrandtl number, $\equiv \nu/\alpha$ fFin \dot{q} Heat generation per unit volume (W m ⁻³)HSHeat sink \vec{q} Heat flux vector (W m ⁻²)hHot side of TE elementQHeat transfer rate (W)LExternal loadQ_IHeat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE elementQ_sHeat transfer rate for the fully developed flow limit (W)nn-type for TE element(W)nn-type for TE elementRElectric resistance (\Omega)optOptimumSSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric elementT_wSurface temperature of the fins (K)tTotal heat sink heat transfer area		Δp	Pressure drop across the heat sink (N m ⁻²)	F	Fluid	
		Pr	Prandtl number, $\equiv \nu/\alpha$	f	Fin	
		ġ	Heat generation per unit volume (W m^{-3})	HS	Heat sink	
QHeat transfer rate (W)LExternal load Q_l Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limitmaxMaximum(W)nn-type for TE elementRElectric resistance (Ω)optOptimumSSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric elementT_wSurface temperature of the fins (K)tTotal heat sink heat transfer area		\overline{q}	Heat flux vector (W m^{-2})	h	Hot side of TE element	
Q_l Heat transfer rate for the boundary layer flow limit (W)lossHeat loss from the side surfaces of the TE element Q_s Heat transfer rate for the fully developed flow limitmaxMaximum(W)nn-type for TE element R Electric resistance (Ω)optOptimum S Seebeck coefficient (V K ⁻¹) p p-type for TE element T Absolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K) t Total heat sink heat transfer area		Q	Heat transfer rate (W)	L	External load	
Q_s Heat transfer rate for the fully developed flow limit (W)maxMaximum n-type for TE elementRElectric resistance (Ω)optOptimumSSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K)tTotal heat sink heat transfer area		Q_l	Heat transfer rate for the boundary layer flow limit (W)	loss	Heat loss from the side surfaces of the TE element	
(W)nn-type for TE elementRElectric resistance (Ω) optOptimumSSeebeck coefficient $(V K^{-1})$ pp-type for TE elementTAbsolute temperature (K) TEThermoelectric elementT_wSurface temperature of the fins (K) tTotal heat sink heat transfer area		Q_s	Heat transfer rate for the fully developed flow limit	max	Maximum	
RElectric resistance (Ω)optOptimumSSeebeck coefficient (V K ⁻¹) p p -type for TE elementTAbsolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K) t Total heat sink heat transfer area			(W)	п	n-type for TE element	
SSeebeck coefficient (V K ⁻¹)pp-type for TE elementTAbsolute temperature (K)TEThermoelectric elementT_wSurface temperature of the fins (K)tTotal heat sink heat transfer area		R	Electric resistance (Ω)	opt	Optimum	
T Absolute temperature (K)TEThermoelectric element T_w Surface temperature of the fins (K)tTotal heat sink heat transfer area		S	Seebeck coefficient (V K ⁻¹)	р	p-type for TE element	
T_w Surface temperature of the fins (K) t Total heat sink heat transfer area		Т	Absolute temperature (K)	TE	Thermoelectric element	
		T_w	Surface temperature of the fins (K)	t	Total heat sink heat transfer area	

improving energy recovery efficiency and system efficiency [19,20], and enhancing chemical reactions [21,22]. Moreover, several studies [23,24] have shown the promising potential of using TEGs for waste heat recovery. Meng et al. [25] proposed a TEG model with multi-irreversibilities; they suggested that the results could be regarded as the feasibility reference using the waste heat for power generation. Because there is almost no cost for obtaining waste heat, the low efficiency problem of TE devices is not a critical issue [24].

Some studies have optimized the geometric design of TE devices. A numerical optimization of a TEC was presented by Xuan [26]. The results indicated that the construction cost of a TEC was closely related to the cooling power density, whereas the running cost was inversely proportional to COP. Kubo et al. [27] altered the size of incisions along the lateral faces of a TE device; they found that the relationship between the TE performance and the incision size depended on the cold side temperature. Yilbas and Sahin [28] introduced two parameters, the slenderness ratio and the external load parameter, to analyze the TEG efficiency; their results showed that the higher efficiency could be obtained for almost all the external load parameters considered when the slenderness ratio was less than 1. Jang et al. [29] optimized the design of micro-TEGs using finite element analysis. High efficiency was obtained when the length of the thermoelements was large. In addition, the power generated declined with the cross-sectional area of the thermoelements, whereas efficiency showed the opposite trend.

A review of the literature shows that the design of the geometry plays an important role in optimizing the performance of TEGs. However, few studies have reported on the optimization of geometry design of TEGs incorporated with air-cooling system. An air-cooling system combined with a heat sink is commonly used for dissipating the heat produced by electronic devices due to its low unit price, low weight, and high reliability [30]. Accordingly, the objective of the present study is to investigate the characteristics of TEGs with an air-cooling design where a finite element method is used to predict the performance of the TEGs. The effects of the heat sink geometry and TEG dimensions on performance are taken into account. To improve the performance of the TEGs, twostage optimization is carried out. Specifically, an analytical method is used to model the air-cooling system, followed by employing a method of compromise programming to seek the optimal performance of TEGs.

2. Mathematical formulation and modeling

Numerical simulations are adopted to predict the performance of TEGs. The physical and numerical models are described below.

2.1. Assumptions

To simplify the TEG system, the following assumptions are made:

Download English Version:

https://daneshyari.com/en/article/1734340

Download Persian Version:

https://daneshyari.com/article/1734340

Daneshyari.com