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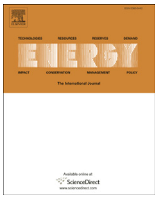

Temperature distribution, local and total entropy generation analyses in asymmetric cooling composite geometries with multiple nonlinearities: Effect of imperfect thermal contact

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ABSTRACT

Entropy generation, which is available exergy destruction, is an important subject in fields of energy management and thermal engineering. With the fast-growing rate of composite media applications in both industries and academic researches, it is necessary to study these media from the second law of thermodynamics point of view. In this work, three fundamental composite media, i.e., composite walls, cylinders and spheres, are considered. The thermal contact resistance between two layers of each medium is considered to be non-zero, and the effect of the radiation heat loss from the second layer, i.e., the outer layer of the composite system, is taken into account. Thermal conductivities are assumed temperature-dependent. Temperature-independent internal heat generation within each layer is considered. The system of non-linear ordinary differential equations is solved with a combined analytical–numerical technique. Assuming temperature-independent thermal conductivities and neglecting the radiation effect, the system of ordinary equations can be solved with an exact analytical technique. Finding the solution of the temperature distribution and local entropy generation rate with this exact analytical procedure, provides a practical tool to check the correctness and accuracy of the combined analytical–numerical solution for general problems, i.e., with the radiation effect and temperature-dependent thermal conductivities. Thereafter, temperature distribution, local and total entropy generation rates are plotted for number of parameters for three considered composite geometries. It is found that assuming zero thermal contact resistance overestimates the total entropy generation rate within these composite media. Depending on the value of parameters, it is or is not possible to find an optimum value for the radiation parameter to minimize the total entropy generation rate within these media.

1. Introduction

Multidisciplinary actions to intensify or lessen the heat transfer in thermofluidic systems are nowadays in the core of academic researches [1]. While heat transfer is in close relation to the first law of thermodynamics, the second law of thermodynamics is a practical tool to measure the entropy generation rate within a system or process. A heat transfer process can be optimized quantitatively using the first law of thermodynamics, i.e., energy quantity point of view. The scenario is different when a process should be optimized within the framework of the second law of thermodynamics. The second law of thermodynamics brings about appreciable tool to calculate the irreversibility of the system, viz., the exergy destruction and entropy generation. Therefore, it gives researchers the possibility to optimize a system or process qualitatively not quantitatively [2]. For example, enhancement of heat transfer from heat exchangers can be done using various profiles [3,4] or by optimizing its volume or the heat transfer coefficient [5]. Minimum entropy generation design of a specific fin can be done by employing the second law of thermodynamics [6] and is different from classical optimization methods discussed in Ref. [5]. Needless to emphasis that the configuration obtained from the heat transfer optimization is different from the resultant configuration by the entropy generation minimization (EGM).

All thermal processes involve irreversibilities and incur an efficiency loss. In heat transfer processes the entropy production may be result of any modes of heat transfer, i.e., conduction [7],

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Nomenclature

a_1	slope of the thermal conductivity–temperature curve for inner material, K^{-1}
a_2	slope of the thermal conductivity–temperature curve for outer material, K^{-1}
h_1	convection heat transfer coefficient at the inner surface, $\mathrm{W\ m^{-2}\ K^{-1}}$
h_2	convection heat transfer coefficient at the outer surface, $\mathrm{W\ m^{-2}\ K^{-1}}$
k_1	reference thermal conductivity for inner material, $\mathrm{W\ m^{-1}\ K^{-1}}$
k_2	reference thermal conductivity for outer material, $\mathrm{W\ m^{-1}\ K^{-1}}$
k_{r}	thermal conductivities ratio
Nc_{l}	Biot number at the inner surface
Nc_{r}	Biot number at the outer surface
Nr_{r}	radiation parameter at the outer surface
Q_1	dimensionless volumetric internal heat generation rate for the inner material
Q_2	dimensionless volumetric internal heat generation rate for the outer material
$\dot{q}_1$	volumetric internal heat generation rate for the inner material, $\mathrm{W\ m^{-3}}$
$\dot{q}_2$	volumetric internal heat generation rate for the outer material, $\mathrm{W\ m^{-3}}$
R	dimensionless radius
R_3	dimensionless outer radius
R_{c}	thermal contact resistance, $\mathrm{W\ m^{-2}\ K^{-1}}$
R_j	dimensionless interface radius
r	radius, m
r_1	inner radius, m
r_2	interface radius, m
r_3	outer radius, m
T	temperature, K
T_0	base temperature for thermal conductivities, K
T_1	temperature of inner material, K
T_2	temperature of outer material, K
T_{cl}	convective temperature at inner side, K
T_{cr}	convective temperature at outer side, K
T_{rr}	radiative sink temperature at outer side, K
TCR	dimensionless thermal contact resistance
X	dimensionless axial distance
X_j	dimensionless interface distance
x	axial distance, m
x_2	interface distance, m
x_3	outer surface distance, m

Greek symbols

α_1	dimensionless slope of the thermal conductivity –temperature curve for inner material
α_2	dimensionless slope of the thermal conductivity –temperature curve for outer material
ε	emissivity of the outer surface
θ	dimensionless temperature
θ_1	dimensionless temperature of inner material
θ_2	dimensionless temperature of outer material
θ_{cl}	dimensionless convective temperature at inner side
θ_{cr}	dimensionless convective temperature at outer side
θ_{rr}	dimensionless radiative sink temperature at outer side
σ	Stefan–Boltzmann constant, $\mathrm{W\ m^{-2}\ K^{-4}}$

convection [8–10] and radiation [11]. Other important factors are viscous effects [8–10] and magnetic fields [12]. Following work of Bejan [13,14], many works were done regarding entropy generation analyses and minimization. Performing the entropy generation analysis and knowing the component or parameter that is mostly responsible for the exergy destruction, one is able to enhance the efficiency of the system by adjusting the geometrical configuration or the value of a specific parameter. In the view of the entropy generation analysis, most of researches are about natural or forced convection heat transfer [15–19] and less work have been done in connection with conduction heat transfer [20–22].

One of the pioneering work in connection with the entropy generation in pure conductive media was done by Kolenda et al. [23]. It was found in this study that introducing additional heat sources within a conductive medium makes it always possible to optimize entropy generation rates. Aziz and Makinde [24] calculated entropy generation rates for two-dimensional orthotropic pin fins. Convective heat transfer was considered for both lateral surface and tip of the fin. The energy equation was solved analytically using the separation of variables method, and local and total entropy generation rates within the fin material were derived. Sahin [25] investigated the entropy generation rate within slabs for various cases such as constant thermal conductivity, variable thermal conductivity and internal heat generation. Aziz and Khan [26] studied the classical and minimum entropy generation analyses within slabs, hollow cylinders and hollow spheres. To model homogenous or functionally graded materials, the study pertained to temperature or spatial dependent thermal conductivities, respectively. Recently, Aziz and Khan [27] corrected erroneous data in Ref. [28] and mathematically proved that the formulation regarding entropy generation in previous publications [28,29] were not correct. After rigorous mathematical modeling, local and total entropy generation rates were plotted for asymmetric cooled slab with the temperature-dependent internal heat generation [27]. Torabi and Aziz [7] considered hollow cylindrical geometries with the radiation effect. To solve the energy equation and obtain the entropy generation, the differential transformation method was used. Torabi and Zhang [30] evaluated both homogenous and functionally graded slabs with the internal heat generation and radiation effects from the second law of thermodynamics point of view.

Due to various applications and superb advantages of composite structures [31–34], multi-layer geometries can be found in many facilities. As mentioned above, great deal of investigations regarding the entropy generation within mono-layer geometries can be found within literature. Amongst the pure conduction works in relation with the entropy generation few of them deal with composite media. Torabi and Zhang [35] opted in favor of the entropy generation in two-layer composite hollow cylinders. Two cases were analyzed: constant temperature boundary conditions and asymmetric convective cooling boundary conditions. Temperature-dependent thermal conductivity was assumed and internal heat generation was incorporated within the modeling. However, entropy generation in composite media with radiation effects and more importantly with imperfect thermal contact has not been considered in literature. It should be pointed out here the effect of the thermal contact in microscale devices [36] and cryogenics engineering [37] is critical and cannot be omitted in simulations. Therefore, number of indispensable effects in temperature profiles and entropy generation rates posed by imperfect thermal contact within composite structures should be investigated.

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