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Review

Entropy generation in thermal systems with solid structures – A concise review

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ABSTRACT

Analysis of thermal systems on the basis of the second law of thermodynamics has recently gained considerable attention. This is, in part, due to the fact that this approach along with the powerful tools of entropy generation and exergy destruction provides a unique method for the analysis of a variety of systems encountered in science and engineering. Further, in recent years there has been a surge of interest in the thermal analysis of conductive media which include solid structures. In this work, the recent advances in the second law analyses of these systems are reviewed with an emphasis on the theoretical and modeling aspects. The effects of including solid components on the entropy generation within different thermal systems are first discussed. The mathematical methods used in this branch of thermodynamics are, then, reviewed. This is followed by the conclusions regarding the existing challenges and opportunities for further research.

Contents

1. Introduction

Multidisciplinary efforts to achieve better control of the heat transfer rates in thermal systems are currently of significant

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Nomenclature

a_{sf}	interfacial area per unit volume of porous media, m^{-1}
c_p	specific heat at constant pressure, $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
h_{sf}	fluid-to-solid heat transfer coefficient, $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$
J	current density, $\mathrm{amp \cdot m^{-2}}$
k	thermal conductivity of solid material, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
k_{ef}	effective thermal conductivity of the fluid (εk_f), $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
k_{es}	effective thermal conductivity of the solid $((1-\varepsilon)k_s)$, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
N_s'''	dimensionless local entropy generation rate
Q	Dimensionless volumetric internal heat generation rate
$\dot{q}$	Volumetric internal heat generation rate, $\mathrm{W \cdot m^{-3}}$
$\dot{S}_f'''$	local entropy generation rate within the fluid phase of the porous medium, $\mathrm{W \cdot m^{-3} \cdot K^{-1}}$
$\dot{S}_s'''$	local entropy generation rate within the solid phase of the porous medium, $\mathrm{W \cdot m^{-3} \cdot K^{-1}}$
T	temperature, K
T_f	temperature of the fluid phase of the porous medium, K
T_s	temperature of the solid phase of the porous medium, K
t	time, S
u_f	velocity of the fluid in the porous medium, $\mathrm{m \cdot s^{-1}}$
X	dimensionless axial distance
x	axial distance, m
y	vertical distance, m

Greek symbols

σ	electric conductivity, $\Omega^{-1} \cdot \mathrm{m}^{-1}$
ε	porosity
κ	permeability, m^2
μ_f	fluid viscosity, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
μ_{eff}	effective viscosity of porous medium, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
θ	dimensionless temperature
ρ	fluid density, $\mathrm{kg \cdot m^{-3}}$

academic and industrial interest [1]. This mainly stems from the rapidly growing concerns about energy efficiency in a wide range applications spanning from industrial to domestic appliances [2]. Further, the introduction of micro and bio-heat transfer and energy technologies has set new challenges for the thermal energy optimization [3–5]. Fundamentally, heat transfer has close ties with the first law of thermodynamics and this is, effectively, the only thermodynamic principle used in conventional heat transfer analysis. The second law of thermodynamics provides a measure of entropy generation rate, or irreversibility, within a system or process, and as a result, impacts the efficiency of the heat transfer process. Over the last few decades, there has been an increasing awareness about the influence of irreversibility on energy interactions [6]. This has led to the formulation of exergy analysis and the definition of exergetic efficiencies as an addition to the conventional energy efficiency approach [2,6,7]. Although initially developed for thermo-mechanical processes, the concept of exergy was extended to chemical systems as well [8], and it is now being applied to the problems in ecology, environment and economy [9,7]. Central to the conduction of exergy analysis is the calculation of entropy generation, which then determines the rate of exergy destruction [10,6]. This evaluates the level of degradation of energy and therefore introduces the concept of energy quality [11]. The first law analysis, however, does not recognize the variations in energy quality and only conducts an energy accounting [12]. This difference is the principal reason for the veracity of second law analyses when compared to those, which are solely on the basis of the first law of thermodynamics.

Application of second law analysis in thermal engineering, provides the possibility of optimizing a given system or process on the basis of the energy quality, which is very different from a first law analysis [13]. For example, it is well documented that the heat transfer in heat exchangers can be enhanced using various profiles of extended surfaces [14,15], or by optimizing the volume flow rate or the heat transfer coefficient [16]. However, design of a specific fin on the basis of the minimum entropy generation [17] results in different configurations compared to those obtained by the classical optimization methods [16]. This is also true when one is applying the concept of entropy generation to optimize the temperature field in electronic devices [18]. These types of thermodynamic analyses, i.e., the entropy generation and exergy analyses of a system, have been interestingly further extended to exergetic analysis of the human body [19,20]. Even for the human body, the obtained results from the energetic and the exergetic analyses were quite different to each other [19], which leads researchers to re-consider thermal systems by using the perspective of the second law of thermodynamics. This has been extended further to the consideration of the second law of thermodynamics over the first law for mechanical analysis in solid structures [21,22]. For instance, Baneshi et al. [21] used maximum entropy generation criterion to calculate the worst case scenario for mechanical systems under thermomechanical loads.

In reality, all thermal processes include some level of irreversibility, primarily due to the existence of temperature gradients. This renders an exergetic efficiency loss and results in reducing in the energy quality. In heat transfer processes, entropy generation has been reported in conduction [23–26], convection [27–29], radiation [30,31], and/or any combination of these modes of heat transfer [32,33]. Further, there are other sources of irreversibilities such as viscous dissipation [27–29] and magnetic fields [34]. Initiated by the seminal works of Bejan [35,36], several studies have been conducted on the minimization of entropy generation [37–41,10,12,42]. To date, there has been a significant focus on exergetic processes in forced and free convection [37–41,10,12,42]. However, much less attention has been paid to the entropy generation in heat conductive media [43–45]. Given that solid structures are found in, nearly all thermal systems, this field has major potentials to grow, and is still far from maturity. Perhaps more importantly, after the introduction of complex solid components into thermo-mechanical systems, such as composite and multilayer structures, the first and second law analyses of conductive systems has gained considerable attention [46–48]. Hence, obtaining

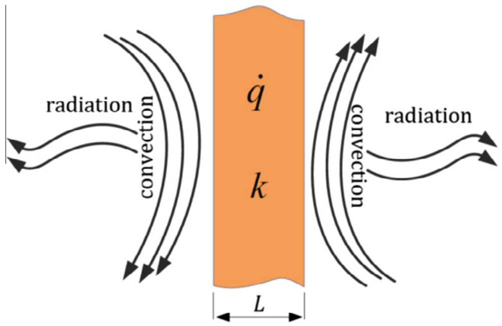

Fig. 1. Configuration of a solid wall with different modes of heat losses.