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Assessment of two different optimization principles applied in heat conduction

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Abstract Optimization principles play a crucial role in the intensification of the heat-transfer process. In this study, we assess and compare two principles, i.e., the entransy dissipation extremum (EDE) principle and the minimum entropy generation (MEG) principle, used in a typical "area to point" heat conduction problem solved via a cellular automaton algorithm. The simulated results indicate that both rules can ameliorate the tree-network conductive path, leading to a more uniform thermal field and lower average and maximum temperatures. In contrast to the MEG principle, the EDE principle is more appropriate to be linked to the algorithm when dealing with the "area to point" heat conduction optimization, especially with a higher conductivity ratio, k_p/k_0, between the high conductivity material and the low conductivity material and the fraction of high conductivity, ϕ_0. With the analysis of total entransy dissipation rate and entropy generation of the domain optimized by two principles, the results indicate that the EDE principle is more suitable for the heat-transfer processes without heat–work conversion. Moreover, optimization via reducing the total entransy dissipation rate exhibits better performance in decreasing the equivalent resistance theoretically.

Keywords Heat conduction · Entransy dissipation · Entropy generation · Optimization principle · Cellular automaton

1 Introduction

Almost all energy utilization involves a heat-transfer process; thus, intensifying this process is of great significance for energy conservation. To describe heat-transfer processes, many scholars have proposed several physical quantities. Bejan [1–3] noted that entropy generation represents the irreversibility of the system resulting from heat transfer and flow resistance. However, several researchers have indicated that entropy generation might be closely related to the conversion of heat energy to work but not to a heat-transfer process [4–6]. In view of these findings, more effort is required to characterize the heat-transfer process. Guo et al.'s work [7] is noteworthy in that it developed rigorous methodology to describe the heat-transfer ability via an analogy between heat transfer and electric conduction. In the theory of Guo, the concept of entransy was explicitly presented to depict the capability of heat transfer, and the dissipation of entransy was demonstrated to represent the reduction in heat-transfer ability.

On the basis of the aforementioned physical quantities, there are generally two principles involved in the intensification of heat-transfer processes: One is minimum entropy generation (MEG), cited as thermodynamic optimization [1–3], and the other is entransy dissipation extremum (EDE), cited as heat-transfer optimization [7]. San et al. [8] studied entropy generation in convective heat transfer within a smooth channel under different thermal boundary conditions. Tondeur and Kvaalen [9] proposed

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that the heat-transfer process could be improved via a uniform distribution of a function of entropy generation as far as possible, such that the uniform distribution could lead to minimal total entropy generation. Li et al. [10] applied the MEG principle to optimize the convective heat transfer for a solar receiver. Ordonez and Bejan [11] optimized a parallel-plate ideal gas counter flow heat exchanger by the MEG principle. Azoumah et al. [12] and Johannessen and Kjelstrup [13, 14] optimized reactors for a variety of industrially relevant reactions via the MEG principle. In addition, David et al.'s [15] study optimized a heat pump system by minimizing the entropy generation. Jankowski [16] and Ratts and Raut [17] used the MEG principle in various internal flow optimization studies. More recently, Tarlet et al. [18] used infrared thermography to quantify and discuss the intensifying effects of transverse baffles on a mini heat exchanger via the global heat-transfer coefficient and the entropy generation. Similarly, the EDE principle has also been well developed via the unremitting efforts of many scholars. Chen et al. [19] and Wei et al. [20] applied the EDE principle to optimize the "volume to point" heat-transfer process. Cheng et al. [21] demonstrated that entransy would decrease in the heat-transfer process of an isolated system. Açıkkalp [22] investigated an irreversible heat pump via entransy analysis and performance criteria. Recently, Feng et al. [23, 24] and Yang et al. [25] made the optimizations based on entransy dissipation extremum principle in many other practical areas, such as the insulation layer of the steel rolling reheating furnace wall or the solidification heat-transfer process of slab continuous casting. Besides, Chen [26] even expanded the concept of entransy to mass transfer process. However, there is still no consensus on the acceptable optimization principle applied to heat-transfer enhancement; thus, its application is consequently restricted. Therefore, it is apparently necessary to make an assessment and comparison between the optimization principles for heat-transfer enhancement. Fortunately, some recent progress has been made toward this goal. For example, Chen et al. [27] compared MEG and EDE principles for a 2D convective heat-transfer process. Their results indicated that the EDE principle is more suitable for intensifying the convective heat-transfer process without heat–work conversion, which shows good agreement with the results of previous studies [4–6]. Chen et al. [28] optimized a heat exchanger couple via entransy dissipation and entropy generation. The results showed that the EDE principle corresponds to the minimum thermal resistance principle and is more suitable than the MEG principle for such a problem. Cheng and Liang [29] applied entropy generation and heat entransy loss to analyze the heat–work conversion and heat-transfer processes. Wang et al. [30] and Cheng and Liang [31] applied the concept of entransy dissipation and entropy generation to analyze the endoreversible Carnot cycle and heat pump system, respectively. In addition, a review has been made via Cheng and Liang [32] in which the difference between the entransy theory and the minimum entropy generation principle was discussed.

However, the assessment and comparison of these two principles used in the heat conduction process through solid phases, which is also important in many fields [19, 20, 33–45], appear to have been neglected. This observation is the basis of the present work, which compares two principles optimizing the process of heat conduction. For this purpose, a meaningful 2D "area to point" model is discussed that has been widely studied for years because of its significance for electronic engineering or microelectronic devices. Generally speaking, the devices, such as electronic chips, can be modeled as a 2D surface. Due to the detriment to the device of the heat generated, the 2D issue of how to cool the heat-generating surface has attracted increasing attention. One possible solution is to assign a reasonably high conductivity material in the heating surface (a conductive path) to remove the generated heat to the heat sink with a lower temperature [33–35, 37–46]. Among the diverse methods to mitigate this problem, the cellular automaton method adopted by Boichot et al. [44, 45] is easily programmed and conveniently visualized for the shaped conductive path after iteration, during which a thermal gradient is treated as the rule. The definition of the rule facilitates the combination of optimization principles and this algorithm. In this work, instead of the thermal gradient, the entransy dissipation of the EDE principle and the entropy generation of the MEG principle are defined as the governing rules of the algorithm. The distinct optimal results due to these two rules enable us to analyze the applicability of different principles in the heat conduction process. In summary, the objective of the present work is to assess and compare the EDE and MEG principles used to optimize the 2D "area to point" heat conduction process by the cellular automaton algorithm.

2 Numerical modeling

2.1 Computation domain and boundary conditions

As a typical case of "area to point" heat conduction problems, a simplified square domain corresponding to an electron component is chosen as the calculation domain. As shown in Fig. 1, the domain consists of 400 × 400 square cells with a length of 10^{-4} m, and the cells can be classified into four groups:

Heat sink cells: cells that have a low constant temperature and a high thermal conductivity, k_p;