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Research Paper

Optimization of pulsed thermoelectric materials using simulated annealing and non-linear finite elements

P. Moreno-Navarro [a,*], J.L. Pérez-Aparicio [b], J.J. Gómez-Hernández [c]

[a] Sorbonne Universités – Université de Technologie Compiègne, Laboratoire Roberval de Mécanique, Chaire de Mécanique, France
[b] Department of Continuum Mechanics & Theory of Structures, Universitat Politècnica de València, Spain
[c] Research Institute of Water and Environmental Engineering, Universitat Politècnica de València, Spain

HIGHLIGHTS

- To find optimal electric intensity pulse for overcooling with thermoelements.
- Heuristic optimization simulated annealing. Non-linear coupled dynamic finite element.
- Multi-objective-parametric: overcooling, uptime, time max. overcooling, overheating.
- Parametric study and coupling with mechanical field to limit maximum stresses.

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ABSTRACT

The objective of this work is to determine the optimal shape, gains and duration of an electric pulse applied to a Peltier cell, together with the length of the thermoelectric to maximize cooling while minimizing electric consumption. For this purpose, a fully coupled, multiphysics, dynamic finite-element model, which solves for the thermal, electric and mechanical fields is used. Because of the demanding computing requirements of the optimization process, a special mesh is designed and a convergence analysis is carried out before using the multiphysics model. The highly non-linear optimization is done by simulated annealing, a heuristic algorithm in the Markov chain Monte-Carlo family. A preliminary parametric investigation is presented, analyzing the impact of some of the parameters. The results of this preliminary analysis help to understand the effect of the different shapes in the evolution of the cold face temperature. Some of these results are expected and have already been discussed elsewhere, but others can only be explained after further analysis and a full system modeling. Pulse optimization is multiobjective and multiparametric, i.e., it can consider several targets such as maximizing the cooling temperature, the cooling duration or others. The trade-offs between the different targets are studied. In all cases, stresses inside the thermoelement are examined at all points, and the pulses must meet the restriction that an equivalent stress is not above the allowable value.

1. Introduction

In spite of the many papers published on pulsed thermoelectrics (PT), the study of the pulse shape itself has attracted limited attention and the most common shape is a step (in reality, slightly trapezoidal), see for instance [1]. Given the advances in quality and price of electric and electronic control equipment, it is pertinent to improve PT's performance and consumption.

The purpose of the present paper is to determine pulse optimal shapes for thermoelectric material (TM) refrigeration with Peltier cells; these pulses will not have a predefined shape but will be within a bounding envelop. The shape is closely related with the thermoelement (TE) length l (of "boxed" parallelepipedal geometry), and the duration of the pulse itself; both of them are input parameters to the optimization algorithm. It will be shown that suitable (although not easy to guess) combinations of shapes and lengths can substantially improve the performance of the Peltier cell, for eight different scenarios.

Recently, [2] considered several predetermined pulses (step, linear and quadratic) to differentiate the overcooling of micro and nanoscales, deciding by inspection, the two best pulses for each scale. The *Maxwell-Cattaneo* constitutive equations and dissipative flows were considered, with thermal and electric

* Corresponding author.
E-mail address: pablo.moreno-navarro@utc.fr (P. Moreno-Navarro).

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Nomenclature

n	nodes per edge [–]
l	length [m]
x	spatial coordinates [m]
P	pulse gain [–]
T	temperature [°C]
t	time [s]
θ	annealing temperature [–]
λ_a	reduction factor of θ [–]
K	maximum number of iterations [–]
S_p	stopping number [–]
O	objective function [–]
$\boldsymbol{p}$	set of input parameters
$\boldsymbol{\varphi}$	set of weight parameters
$\mathcal{T}$	equivalent stress [MPa]
σ	standard deviation
$\mathcal{S}$	optimization goal

Sub-, supra-indices

i	spatial direction, counter
$\bar{\square}$	prescribed property for $\square$
h	hot side (T), holding (t)
c	cold side
0	reference
ac	accepted
rj	rejected
p	pulse
pp	post-pulse
op	optimal
css	cold face at steady-state
mn	minimum
mx	maximum
I, II, III	principal directions
tr	Tresca
ad	admissible

conductivities as a function of the layer thickness. Also, [3] carried out a parametric study of pulses for refrigeration; no elastic coupling was considered since the models were purely thermoelectric, although the boundary conditions (BC) were realistic with convection in the hot face and constant prescribed heat flux in the cold face. The model was validated and the differences between constant and variable properties studied. No optimization algorithm was applied, instead conclusions were drawn from the extensive parametric set of cases. Another parametric study was presented in [4] analyzing, in a rather simple manner for constant pulses, the influence of parameters such as pulse gain and duration, using a one-dimensional (1D) model. Constant pulses were also analyzed in [5] but an experimental parametric investigation instead of a numerical model was presented. This work was focused more on boundary conditions than on pulse parameters and the pulse train influence was shown as well.

Other types of optimizations have been published. For instance, [6] optimized the material properties and the ratio of TE area and length using simple analytical models and experimental results. In [7,8], cooling applications were optimized, in the former with electric network models and finite elements (FE) for refrigerators, and in the latter with 1D analytical formulae for radiating air conditioning.

In [9], ANSYS was used on a novel and predetermined pulse shape for a practical application; the optimization goals were similar to the ones of the present article. The work presented a parametric study on pulse gain, duration for basic pulse shapes (constant, triangular, ramps), quantifying the overcooling produced by the pulse with respect to the stationary state.

An optimization of a two-stage TM refrigerator with a 1D numerical method was presented in [10], but the optimization was not for the pulse itself but for the positions of the thermocouple (TC). Analytical formulae were developed to calculate the optimal intensity, and based on these, the optimal coefficient of performance (COP) and extracted heat were determined; this was achieved varying the number of TCs and the hot face temperature T_h although in static operation. The articles [11,12] were also related with two-stage refrigerators. In the former, a multiparametric study—changing the heat source, sink and current—is developed, comparing it with experimental results. In the latter, a more realistic model with convection is run for another multiparametric study, in which the pulse duration, gain and shape as well as basic parameters of the geometry are varied.

Finally, [13] developed a simplified 1D model (not including the *Thomson* effect) based on a *Fourier* sums of eigenvalues, to analytically predict the cold face temperature T_c. The next step was to optimize the distributions of the *Seebeck* coefficient α and electric conductivity γ along the TE (as in graded materials) under a constant pulse. Empirical expressions for maximum overcooling and time to reach it as a function of the pulse gain were developed.

In the current work, it will be assumed that, both for steady and transient states, the intensity is the same for all TCs of the cell; therefore, a single TC is discretized under appropriate BC. The cold face is subjected to a cooling optimal intensity calculated from semi-analytical formulae taken from [14] prior to the application of the pulse. The hot face is considered attached to an infinite medium so that its temperature remains constant at $\overline{T}_h = 50\,°\mathrm{C}$. Regarding the mechanical BC, both hot and cold faces are mechanically hinged. To reduce the FE mesh, two planes of symmetry and a plane of repetition will be applied.

The FE model, developed in [15–17], has been shown to be very efficient for the modeling of cooling using Peltier cells. `FEAP`, a research code with special elements developed by [18] is used.

The optimization model is heuristic in nature, which is both an advantage and a shortcoming; an advantage, because it will search for global optimal solutions, avoiding local optima, and a shortcoming, because it requires many runs of the FE model needing much CPU time to reach the optimum. This optimization algorithm was chosen for its power to minimize complex functions involving non-linearities, fully coupled processes, system dynamics and 3D geometry without imposing any restrictions in the potential outcomes.

In Fig. 1, a conceptualization of the temperature T_c evolution at the cold face is shown. From the steady-state T_{css} and after a pulse of gain P is applied at time t_{ss} (set to zero), the temperature descends drastically until it reaches a minimum $T_{css} - \Delta T_p$ at time t_{mn}; this is the transient overcooling phase. Close to the end of the pulse, of duration t_p, the temperature bounces back and reaches a value $T_{css} + \Delta T_{pp}$ (both ΔT_p and ΔT_{pp} are positive); this is the transient overheating phase. If no other pulse is introduced, the temperature slowly lowers back to the initial T_{css}. The description and related dynamic calculations of a PT have thoroughly been studied in [14].

Before launching the optimization algorithm and its thousands of runs, a convergence study of the fully coupled FE code is performed in Section 2. The usefulness of this convergence study is