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Entransy theory for the optimization of heat transfer – A review and update

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ABSTRACT

Heat transfer optimization methods to effectively improve heat transfer performance is of great importance for energy conservation and pollution reduction. A recently developed heat transfer optimization method based on entransy theory and related peer-reviewed papers published between 2003 and 2010 are reviewed and updated in this paper to describe entransy, entransy dissipation, optimization criteria and optimization principles and their applications to different heat transfer modes (thermal conduction, convection and radiation) and to different levels (heat transfer element, heat exchanger, and heat exchanger network). Entransy theory is then compared with entropy theory in several aspects, including the heat transfer purpose, irreversibility and optimization principle for energy savings or weight reductions of thermal facilities. Finally, entransy theory is also compared with constructal theory in terms of optimization objective, optimization method and optimized results.

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Nomenclature

$A, B, C, C_0, A', B', C', C'_0$	Lagrange multipliers
c	speed of light in vacuum, m s^{-2}
c_p	constant pressure specific heat capacity, J kg^{-1} K^{-1}
c_v	constant volume specific heat capacity, J kg^{-1} K^{-1}
E_e	electrical potential energy in a capacitor, J
E_g	gravitational potential energy of fluid in a vessel, J
E_h	potential energy of a phonon gas, J
e_h	density of potential energy of a phonon gas, J m^{-3}
$\dot{e}_h$	pontential energy flux of a phonon gas, W m^{-2}
F	additional volume force for laminar heat transfer, N m^{-3}
F_t	additional volume force for turbulent heat transfer, N m^{-3}
f	friction factor
G	entransy, J K
g	specific entransy, J K m^{-3}; gravitational acceleration, m s^{-2}
$\dot{g}$	entransy flux, W K m^{-2}
$\dot{g}_r$	radiative entransy flux, W^2 m^{-4}
H	height, m
K	heat exchanger heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
k_e	electrical conductivity, S m^{-1}
M	mass, kg
$\dot{M}$	mass flow rate, kg s^{-1}
M_h	thermomass, kg
Nu	Nusselt number
$\vec{n}$	unit vector
P	pressure, Pa
Pr	Prandtl number
Q_{ve}	electrical charge stored in a capacitor, C
Q_{vh}	thermal energy stored in an incompressible body, J
$\dot{Q}$	heat transfer rate, W
$\dot{Q}_t$	total heat exchange rate in a heat exchanger, W
$\dot{q}$	heat flux, W m^{-2}
$\dot{q}_e$	electrical current density, A m^{-2}
Re	Reynolds number
R_h	thermal resistance, K/W
$\dot{S}_q$	internal heat source, W m^{-3}
$\dot{S}_{hg}$	internal entransy source, W K m^{-3}
$\dot{S}_g$	entropy generation rate, W K^{-1}
$\dot{s}_g$	entropy generation rate per unit area during thermal radiation, W K^{-1} m^{-2}
T	temperature, K
U	internal energy, J
U_e	electrical potential, V
U_h	thermal potential, K
U_{hr}	radiative heat flux potential, W m^{-2}
$\vec{U}$	velocity vector, m s^{-1}
$\overrightarrow{U_h}$	velocity vector of a phonon gas, m s^{-1}
V	volume, m^3
u, v, w	velocity components in x, y and z directions, m s^{-1}
x, y, z	Cartesian coordinates, m

Greek symbols

ε	emissivity
η	uniformity factor for a temperature difference field
λ	Lagrange multiplier
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
ρ_h	thermomass density, kg m^{-3}
σ	Stefan–Boltzmann constant, W m^{-2} K^{-4}
τ	time, s; viscous force, N m^{-2}
$\dot{\Phi}_g$	entransy dissipation rate, W K
$\dot{\phi}_e$	dissipation rate per unit volume of the potential energy of a phonon gas, W m^{-3}
$\dot{\phi}_g$	entransy dissipation rate per unit volume, W K m^{-3}
$\dot{\phi}_m$	viscous dissipation rate per unit volume, W m^{-3}

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1. Introduction

Heat transfer is thermal energy in transit due to a temperature difference, one of the most common physical phenomena in the world, especially in energy systems. Estimates of all the worldwide energy utilization suggest more than 80% involve heat transfer processes. Thus, improved heat transfer performance offers a huge potential for conserving energy and reducing CO_2 emission so as to reduce global warming [1,2]. During the past several decades, heat transfer science, dealing with analyses of heat transfer rates taking place in systems, has been well developed with a large number of heat transfer enhancement techniques developed to improve the performance of energy generation, conversion, consumption and conservation [1–13]. However, unlike thermodynamics, another thermal science subject, there is no concept of efficiency but only the concept of the heat transfer rate, so scientists and engineers often focus on heat transfer enhancement which is usually associated with increased pumping power and in turn usually reduces the energy utilization efficiency.

Heat transfer is an irreversible, non-equilibrium process from the thermodynamic viewpoint. In a key part of non-equilibrium thermodynamics [14], Onsager [15,16] set up the famous reciprocal relationships for non-equilibrium processes including heat transfer and derived the principle of the least dissipation of energy in terms of the entropy balance equation, where entropy generation is considered to be a measure of irreversibility. Prigogine [17] developed the minimum entropy production principle based on the idea that the entropy production in a thermal system at steady state had to be at the minimum. Both of these principles, however, did not deal with how to improve the heat transfer performance until Bejan [18–23] deduced an expression for the entropy generation to measure the irreversibility of convective heat transfer in viscous fluid flows. Thereafter, many scholars [24–46] have employed the minimum entropy generation as an objective function, and some of them also combined it with optimization