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Development of a new heat transfer optimization method for compressible fluid flows and it numerical verifications

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ABSTRACT

A general optimization criterion for heat transfer process is developed based on the entransy theory. Then, a modified field synergy principle for compressible viscous fluid, which represents the irreversibility of the specific heat transfer processes, is discussed. Modified field synergy equations are set up and theoretically, the solution of the modified field synergy equations under the constraint conditions of a given mean kinetic energy is able to show the optimal flow field, in which the amount of heat transfer is maximized. In the study, a numerical simulation of the heat transfer processes of air in a cavity is selected as the numerical verification of the modified field synergy equations. Numerical simulation results show that asymmetric vortices are generated in the flow field due to the variation of the density. These vortices enhance the heat transfer performance in the absence of too much work dissipation. Comparisons among the results of the Navier–Stokes equations, the existed laminar field synergy equations, and the modified field synergy equations are made. The results confirm that the equations developed in this study correspond to the best heat-transfer performance when the density of fluid changes with temperature or pressure.

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1. Introduction

More than 90% of all the worldwide energy utilization involves the heat transfer process. That is to say, there is a huge potential for conserving energy on thermal engineering through heat-transfer efficiency techniques. Scholars have been working for centuries seeking for the efficient ways to improve the heat transfer performance. During the last several decades, a large number of convective heat-transfer enhancement technologies have been developed including using extended surfaces, spoilers, stirrers, and external electric or magnetic field [1–3]. These trials have successfully reduced energy consumption and retrench expenditure of equipment, but the mechanism of heat transfer process is still unclear. Indeed, none of these analyses adequately explain the principle of heat transfer enhancement, and engineering heat transfer is still considered to be an experimental problem.

In the 1980 s, Bejan [4,5] introduced the entropy generation function for estimating the irreversibility of convective heat-transfer processes in a system along finite temperature gradient with viscous effects. Then convective heat-transfer processes were optimized with the objective of minimum entropy generation. The minimum entropy generation principle is well accepted and widely used in processes analysis and system optimization [6–8]. As time goes by, people found that the entropy generation could not always reach its minimum value when the system performs best, and this weird phenomenon was called “the entropy generation paradox” by Bejan himself. The entropy generation paradox shows that problems may occur during the usage of entropy generation to describe the irreversibility of the heat transfer process in heat exchangers [9–11]. A recent published research indicates that the entropy generation results as a maximum when it is evaluated by the exterior surroundings of the system and a minimum when it is evaluated within the system [12]. The system considered was a typical energy transduction system, that is to say, the paradox found in the heat exchanger system hasn’t been explained.

Another way to consider the possibility of heat transfer optimization is the definition of entransy [13,14]. In this theory, entransy is defined as the heat transfer ability. It is found that in

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Nomenclature

A	Lagrange multiplier, K^{-1}
B	Lagrange multiplier, $J\,kg^{-1}$
C_0	Lagrange multiplier, constant
c_p	specific heat at constant pressure, $J\,K^{-1}$
c_v	specific heat at constant volume, $J\,K^{-1}$
D	Lagrange multiplier
$\boldsymbol{F}$	additional force
G	entransy, J K
g	entransy rate, $J\,K\,m^{-2}\,s^{-1}$
k	conductivity, $W\,m^{-1}\,K^{-1}$
p	pressure, Pa
Q	heat, J
q	heat flux, $J\,m^{-2}\,s^{-1}$
r	gas constant, $J\,kg^{-1}\,K^{-1}$
T	temperature, K
t	time, s
U	internal energy of the body, $J\,kg^{-1}$
v_x, v_y, v_z	velocity component on x, y, z direction, $m\,s^{-1}$
$\boldsymbol{v}$	velocity, $m\,s^{-1}$

Greek symbols

δ	variation operator
μ	viscosity, Pa s
μ'	second viscosity, Pa s
ρ	density, $kg\,m^{-3}$
Φ	dissipation rate, J

Subscripts

c	cooling side
e	external source
h	heating side
$heat$	heat transfer process
in	inlet
m	modified
mom	momentum
out	outlet
t	total value
v	constant volume
w	volume change
τ	viscous dissipation

the irreversible processes entransy is dissipated and heat transfer capability attenuates [15]. This phenomena leads to the extreme entransy dissipation principle: the extreme entransy dissipation corresponds to the minimum transfer resistant for a given heat-transfer problem. The entransy dissipation of a heat transfer process can serve as a judgment of the performance of heat exchanger. Based on this theory, several types of heat-transfer processes, including heat conduction [14], convective heat transfer [15,16] and thermal radiation [17], have been analyzed and optimized numerically. The scholars want to extend this theory into a much more extreme condition to show the general applicability of it, but according to the author's knowledge, the deductions and applications published are all under an incompressible assumption.

The variable-property of fluid may greatly improve the system performance if the system is carefully designed. A good example is the supercritical fluid. The densities of a supercritical fluid are subject to change when pressure or temperature is tampered with. This changing of properties makes supercritical fluid disparate from regular fluids, and thus become a favorite in heat transfer enhancement and thermodynamic cycles for efficiency improvement [18–20]. Thanks to the mature development of modern computation technology, e.g., the computational fluid dynamics and numerical heat transfer methods, robust treatment on the variable-property flow and heat transfer problems could be implemented. In the last decade, the effects of temperature-dependent fluid property were emphasized in many numerical researches, even in micro scale and pore-scale [21–24]. These simulations portrayed the flow details and showed the advantages of the variable-property.

From the aforementioned discussion, the concept of entransy has been developed and leads to a method for convective heat-transfer optimization. Chen et al. [25] investigate the physical essential and the applicability of the extreme entransy dissipation principle in convective heat-transfer optimization. And developed field synergy equation for laminar (LFSE) and turbulent (TFSE) [16] heat transfer processes. By solving the field synergy equation under a specific viscous dissipation value, the optimal flow field can be obtained. According to the theory, the optimal flow field indicates the flow pattern when the heat transfer rate is maximized, which gives a guidance to the further industrial application. However, all the discussions up to now are based on a constant volume assumption, which means the fluids considered in these researches are all incompressible. Researching results showed that the flow and heat transfer performance maybe very different from the regular ones because of the high compressibility [26,27]. When the fluid is compressible, vortexes are generated even when the inlet Reynolds number is not very high, which may either enhance or subdued the heat transfer performance [28]. This phenomenon is interesting as well as disturbing, since we don't know which kind of vortexes can lead to a better heat transfer performance. The current field synergy equations can give an optimal flow field only under the incompressible assumption, so we want to make a complement of the current entransy discussion and extend to compressible fluid and variable fluid properties.

The current study is an extended analysis of the optimization method of a compressible heat transfer process. It's an attempt to develop the existed entransy theory and the laminar field synergy equations. The optimization criteria for the heat transfer process of compressible viscous fluid with variable physical properties have been stated. We introduce the modified field synergy equations by presenting reasonable derivations under the assumption of compressible flow and variable physical properties. By solving the modified field synergy equations, the flow pattern corresponding to the maximum heat transfer rate under a constant viscous dissipation can be obtained. Numerical verifications are done to optimize the heat transfer processes of air in cavity by using the CFD method. It's hoped the models and methods developed could bring a different view in the heat transfer optimization.

2. Theoretical and mathematical models

2.1. Optimization criteria for the heat transfer process of compressible viscous fluid

This part needs to be discussed first because the later derivation is based on the definition of the optimization criteria. As it's said before, the existed discussions of entransy theory are all under the assumption of constant volume, and the criteria of extreme entransy dissipation were used to obtain the optimized flow field in the former works [16]. When it comes to the compressible fluid,

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