INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 6, Issue 4, 2015 pp.391-402
Journal homepage: www.IJEE.IEEFoundation.org

Constructal complex-objective optimization of electromagnets based on maximization of magnetic induction and minimization of entransy dissipation rate

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Abstract
An electromagnet requests high magnetic induction and low temperature. Based on constructal theory and entransy theory, a new complex-objective function of magnetic induction and mean temperature difference to describe performance of electromagnet is provided, and the electromagnet has been optimized using the new complex-objective function. When the performance of electromagnet achieves its best, the solenoid becomes longer and thinner as the number of the high thermal conductivity cooling discs increases. Simultaneously, the magnetic induction becomes higher and the mean temperature difference becomes lower. The optimized performance of electromagnet is also improved as the volume of solenoid increases. Simultaneously, as the volume of the electromagnet increases, the magnetic induction increases to its maximum and then decreases, but the mean temperature decreases all along.

Keywords: Constructal theory; Electromagnet; Complex-objective optimization; Entransy dissipation rate.

1. Introduction

Constructal theory generated at the study of configuration of flow system [1-13]. The constructal law was stated as follows: For a flow system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the current that flow through it. The heat transfer system is an important research area for constructal theory, and the development of constructal theory proposes a new way for the research of heat conduction and convective heat transfer [14-37].

Maximum temperature is usually taken as the optimization objective in heat transfer optimization. The minimization of maximum temperature reflects the optimization result of local part (the hot spot), not the optimization result of the whole system. Some scholars used finite-time thermodynamics or entropy generation minimization (EGM) [38-43] to optimize heat transfer processes. Entropy generation minimization is a heat transfer optimization aiming at exergy lost minimization. Entropy is the measure of the conversion extent from heat to work, and entropy production is the measure of the reduction of the doing work capability due to the irreversibility of the process. The principle of minimum entropy production indicates that the stationary nonequilibrium state is characterized by the minimum entropy production. All these concepts are discussed from the viewpoint of thermodynamics. However, what the heat conduction concerned with is the heat transport efficiency [44]. To solve this shortage in current heat transfer theory, Guo *et al*.[44] defined heat transfer potential capacity and heat transfer potential capacity dissipation function to describe the heat transfer ability amount and its dissipation rate in the heat transfer process. In terms of the analogy between heat and electrical conductions, Guo *et al*. [45] validated that heat transfer potential capacity is a new physical quantity describing heat transfer ability which is corresponding to electrical potential energy:

$$E_{vh} = \frac{1}{2} Q_{vh} U_h = \frac{1}{2} Q_{vh} T \tag{1}$$

where $Q_{vh} = Mc_v T$ is the thermal energy or the heat stored in an object with constant volume which may be referred to as the thermal charge, U_h or T represents the thermal potential. Heat transfer analyses show that the entransy of an object in a capacitor describes its heat transfer ability, as the electrical energy in a capacitor describes its charge transfer ability. Entransy dissipation occurs during heat transfer processes, as a measurement of the heat transfer irreversibility with the dissipation related thermal resistance. Biot [46] introduced a similar concept in the 1950s in his derivation of the differential conduction equation using the variation method. Eckert *et al*.[47] summarized that Biot formulates a variational equivalent of the thermal conduction equation from the ideas of irreversible thermodynamics to define a thermal potential and a variational invariant. The thermal potential plays a role analogous to the potential energy while the variational invariant is related to the concept of dissipation function. However, Biot did not further expand on the physical meaning of the thermal potential and its application to heat transfer optimization was not found later except in approximate solutions to anisotropic conduction problems. The heat transfer ability lost in heat transfer process was called as entransy dissipation, and the entransy dissipation per unit time and per unit volume was deduced as [45]:

$$\dot{E}_{h\phi} = \dot{q} \cdot \nabla T \tag{2}$$

where $\dot{q}$ is thermal current density vector, and ∇T is the temperature gradient. In steady-state heat conduction, $\dot{E}_{h\phi}$ can be calculated as the difference between the entransy input and the entransy output of the object, i.e.

$$\dot{E}_{h\phi} = \dot{E}_{h\phi,in} - \dot{E}_{h\phi,out} \tag{3}$$

The entransy dissipation rate of the whole volume in the “volume to point” conduction is

$$\dot{E}_{h\phi,V} = \int_V \dot{E}_{h\phi} dv, \quad \dot{E}_{h\phi,A} = \int_A \dot{E}_{h\phi} ds \tag{4}$$

where $\dot{E}_{h\phi,V}$ corresponds to three-dimensional model, and $\dot{E}_{h\phi,A}$ corresponds to two-dimensional model. The equivalent thermal resistance for multi-dimensional heat conduction problems with specified heat flux boundary condition was given as follows [45].

$$R_h = \frac{\dot{E}_{h\phi,V}}{\dot{Q}_h^2}, \quad R_h = \frac{\dot{E}_{h\phi,A}}{\dot{Q}_h^2} \tag{5}$$

where $\dot{Q}_h$ is the whole heat flow (thermal current). The corresponding mean temperature difference was defined as:

$$\Delta \overline{T} = R_h \dot{Q}_h \tag{6}$$

The concepts of entransy and entransy dissipation were used to develop the extremum principle of entransy dissipation for heat transfer optimization: For a fixed boundary heat flux, the conduction process is optimized when the entransy dissipation is minimized (minimum temperature difference), while for a fixed boundary temperature, the conduction is optimized when the entransy dissipation is maximized (maximum heat flux). The extremum principle of entransy dissipation was used in optimization of heat conduction [48,49], heat convection[50-53], radiative heat transfer [54] and heat exchanger [55-58]. The extremum principle of entransy dissipation and its application has also been reviewed by Refs.[59-63].

Chen *et al*. [64] firstly combined the extremum principle of entransy dissipation with constructal theory, and optimized the rectangular element by taking entransy dissipation rate minimization as objective. The optimization results showed that when the thermal current density in the high conductive path is linear with the length, the optimized constructs based on entransy dissipation rate minimization are the same as those based on the maximum temperature minimization, and the mean temperature is 2/3 of the maximum temperature. When the thermal current density in the high conductive path is nonlinear with the length, the optimized constructs based on entransy dissipation rate minimization are different from those based on maximum temperature difference minimization. The constructs based on entransy dissipation rate minimization could reduce the mean temperature more effectively than the constructs based on minimization of maximum temperature.

The multidisciplinary optimization of electromagnet was discussed by Gosselin and Bejan [65], the optimal geometries of electromagnet based on maximum temperature minimization for fixed magnetic induction were deduced. Chen *et al*. [66] made a further multidisciplinary optimization of electromagnet based on entransy dissipation rate minimization. The good performance of electromagnet requests high magnetic induction and low temperature. A complex-objective function based on maximization of magnetic induction and minimization of entransy dissipation rate will be discussed in this paper.

2. Entransy dissipation rate versus electromagnet configuration

A cylindrical coil is taken as an example in this paper. Figure 1 shows the front and side views of the solenoid. A wire is wound in many layers around a cylindrical space of radius R_{in}. The outer radius of the coil is R_{out}, and the axial length is $2L$. The solenoid is considered as a continuous medium in which the electrical current density j is a constant. The electrical current density inside the wire generates a one-dimensional magnetic field on the axis of symmetry of the coil. The heat generation rate per unit volume q''' is constant at the working state.

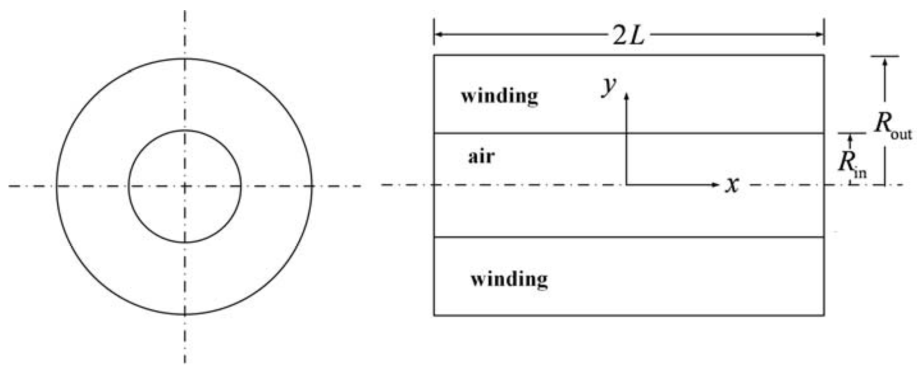

Figure 1. The main features of solenoid geometry [65]

The high thermal conductivity cooling discs of thickness $2D$ are inserted into the solenoid to enhance heat transfer, and the discs are transversal and separate the solenoid into N sub-coils, as illustrated in Figure 2. The fraction of the volume occupied by the discs is known and fixed by

$$\phi = \frac{DN}{L} \tag{7}$$

where N is the number of discs. Most of the volume must be filled by the winding, as required by the drive toward compactness, therefore $\phi \ll 1$. This means that the presence of the discs does not affect significantly the magnetic field. The thermal conductivity coefficient of the material is related to its structure, density, hydrous rate, temperature, etc. But the compactness of the solenoid filled by the winding is not propitious to heat conduction; and the thermal conductivities of the wire insulating materials commonly are: polystyrene 0.08, rubber 0.202-0.29, PVC 0.17, PU 0.25, etc. The thermal conductivity of high thermal conductivity materials commonly are silver 429, copper 401, gold 401, aluminum 237, etc. The thermal conductivity of high thermal conductivity materials is defined as k_p, and the thermal conductivity of the solenoid is defined as k_0, then $k_0 / k_p << 1$. It is assumed that all the boundaries are adiabatic except the exposed external surfaces of the discs, which serve as heat sinks, the heat transfer direction in the k_p material is the x-direction, and the heat transfer direction in the k_p material is the r-direction.

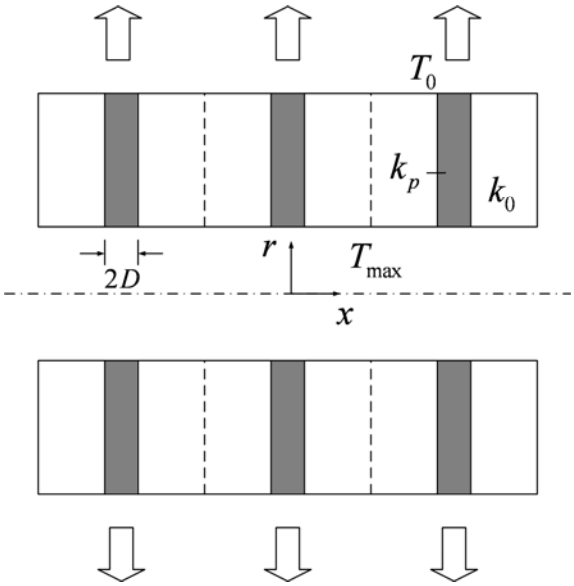

Figure 2. Solenoid cooled by transversal discs with high thermal conductivity [65]

The non-dimensional mean temperature difference based on entransy dissipation rate of solenoid is described as [66]

$$\begin{aligned}\Delta\tilde{\bar{T}} &= \frac{\Delta\bar{T}}{P/(R_{\text{in}}k_0)} \\ &= \frac{q'''R_{\text{in}}^2}{k_0}\left[\frac{2\tilde{L}^3(\tilde{R}_{\text{out}}^2-1)}{3N^2}+\frac{\tilde{L}(3-4\tilde{R}_{\text{out}}^2+\tilde{R}_{\text{out}}^4)}{4\phi\tilde{k}}+\frac{\tilde{L}\ln\tilde{R}_{\text{out}}}{\phi\tilde{k}}\right]\cdot\frac{1}{\left(\tilde{R}_{\text{out}}^2-1\right)\cdot 2}\cdot\frac{R_{\text{in}}k_0}{P} \\ &= \left[\frac{\tilde{L}(\tilde{R}_{\text{out}}^2-1)}{6N^2\pi}+\frac{(3-4\tilde{R}_{\text{out}}^2+\tilde{R}_{\text{out}}^4)}{16\tilde{k}\phi\pi\tilde{L}}+\frac{\ln\tilde{R}_{\text{out}}}{4\tilde{k}\phi\pi\tilde{L}}\right]\cdot\frac{1}{\left(\tilde{R}_{\text{out}}^2-1\right)^2}\end{aligned} \quad (8)$$

The solenoid is constructal optimized based on minimization of mean temperature difference in Ref. [66]. As shown in Figure 3, the minimum mean temperature difference increases as the magnetic induction increases. The optimization results of Ref. [66] were obtained with fixed magnetic induction.

3. Complex-objective function of minimization of entransy dissipation rate and maximization of magnetic induction

For the case of a constant electrical current density j, the magnetic induction is given by [65]

$$\tilde{G} = 0.2\left(\frac{2\pi\tilde{L}}{\tilde{R}_{\text{out}}^2 - 1}\right)^{1/2} \ln\frac{\tilde{R}_{\text{out}} + (\tilde{L}^2 + \tilde{R}_{\text{out}}^2)^{1/2}}{1 + (\tilde{L}^2 + 1)^{1/2}} \tag{9}$$

where

$$(\tilde{R}_{\text{out}}, \tilde{L}) = \frac{(R_{\text{out}}, L)}{R_{\text{in}}} \tag{10}$$

Eqs. (8) and (9) show that the mean temperature difference and magnetic induction are both related to electromagnet configuration. A complex-objective function to describe entransy dissipation rate and magnetic induction is defined as

$$\frac{\tilde{G}}{\Delta\tilde{\tilde{T}}} = \frac{0.2\left(\frac{2\pi\tilde{L}}{\tilde{R}_{\text{out}}^2 - 1}\right)^{1/2} \ln\frac{\tilde{R}_{\text{out}} + (\tilde{L}^2 + \tilde{R}_{\text{out}}^2)^{1/2}}{1 + (\tilde{L}^2 + 1)^{1/2}}}{\left[\frac{\tilde{L}(\tilde{R}_{\text{out}}^2 - 1)}{6N^2\pi} + \frac{(3 - 4\tilde{R}_{\text{out}}^2 + \tilde{R}_{\text{out}}^4)}{16\tilde{k}\phi\pi\tilde{L}} + \frac{\ln\tilde{R}_{\text{out}}}{4\tilde{k}\phi\pi\tilde{L}}\right]\cdot\frac{1}{\left(\tilde{R}_{\text{out}}^2 - 1\right)^2}} \tag{11}$$

The performance of electromagnet requests low entransy dissipation rate and high magnetic induction [54]. Defining $\tilde{G}/\Delta\tilde{\tilde{T}}$ as the optimization objective can satisfy the request. The higher $\tilde{G}/\Delta\tilde{\tilde{T}}$ is, the better the performance of electromagnet is. $\tilde{G}/\Delta\tilde{\tilde{T}}$ is a complex-objective function that can describe the performance of electromagnet. It is the most important improvement of this paper comparing with those in Refs.[65, 66].

A dimensionless volume is defined as [65]

$$\tilde{V} = \frac{V}{R_{\text{in}}^3} = \pi\tilde{L}(\tilde{R}_{\text{out}}^2 - 1) \tag{12}$$

Substituting Eq. (12) into Eq. (11) yields the complex-objective function of maximization of magnetic induction and minimization of entransy dissipation rate

$$\frac{\tilde{G}}{\Delta\tilde{\tilde{T}}} = \frac{(2)^{1/2}\ln\left[\left[\tilde{R}_{\text{out}} + \left[\left(\frac{\tilde{V}}{\pi\left(\tilde{R}_{\text{out}}^2 - 1\right)}\right)^2 + \tilde{R}_{\text{out}}^2\right]^{\frac{1}{2}}\right] \Big/ \left[1 + \left(\frac{\tilde{V}}{\pi\left(\tilde{R}_{\text{out}}^2 - 1\right)}\right)^2 + 1\right]^{\frac{1}{2}}\right]}{5\left[\frac{\tilde{V}^{1/2}}{6N^2\pi^2\left(\tilde{R}_{\text{out}}^2 - 1\right)} + \frac{(3 - 4\tilde{R}_{\text{out}}^2 + \tilde{R}_{\text{out}}^4)}{16\phi\tilde{k}\tilde{V}^{3/2}} + \frac{\ln\tilde{R}_{\text{out}}}{4\phi\tilde{k}\tilde{V}^{3/2}}\right]} \tag{13}$$

4. Optimization of electromagnets

4.1 Maximization of $\tilde{G}/\Delta\tilde{\tilde{T}}$ at different N

$\tilde{G}/\Delta\tilde{\tilde{T}}$ versus $\tilde{R}_{\text{out}}$ at different N is shown in Figure 4. There exists a $\tilde{R}_{\text{out},opt}$ that $\tilde{G}/\Delta\tilde{\tilde{T}}$ achieves its maximum and the performance of electromagnet achieves its best. The bigger N is, the higher $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ is, and the better the performance of the electromagnet is.

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

$\tilde{R}_{\text{out},opt}$ and $\tilde{L}_{opt}$ versus N when $\tilde{G}/\Delta\tilde{\tilde{T}}$ achieves its maximum is shown in Figure 5. $\tilde{R}_{\text{out},opt}$ decreases as N increases, and $\tilde{L}_{opt}$ increases as N increases. When the performance of electromagnet achieves its best, the solenoid becomes longer and thinner as N increases.

When the performance of electromagnet achieves its best, the corresponding $\tilde{G}$ versus N and $\Delta\tilde{\tilde{T}}$ versus N are shown in Figures 6 and 7, respectively. As N increases, the magnetic induction $\tilde{G}$ increases and $\Delta\tilde{\tilde{T}}$ decreases. The magnetic induction ability and heat transfer ability are both improved as N increases.

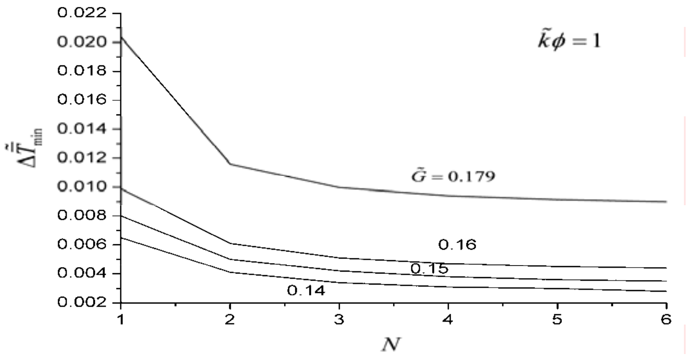

Figure 3. Effect of $\tilde{G}$ on $\Delta\tilde{\tilde{T}}_{\min}$ versus N with fixed $\tilde{k}\phi$ [66]

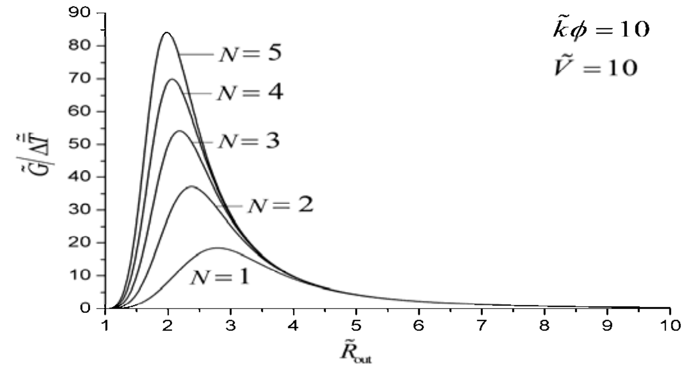

Figure 4. Effect of N on $\tilde{G}/\Delta\tilde{\tilde{T}}$ versus $\tilde{R}_{\text{out}}$ with fixed $\tilde{k}\phi$ and $\tilde{V}$

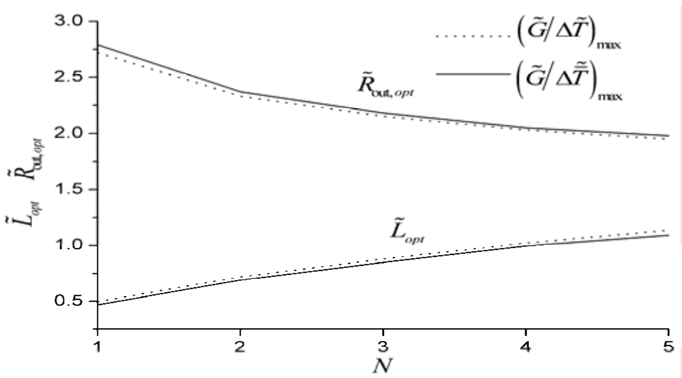

Figure 5. Comparisons between optimal geometries at $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ and $\left(\tilde{G}/\Delta\tilde{T}\right)_{\max}$

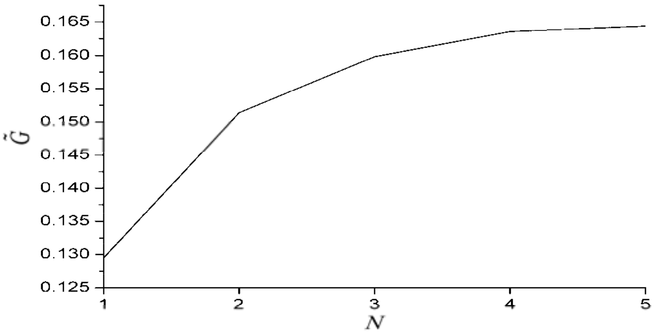

Figure 6. $\tilde{G}$ corresponding to $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ versus N

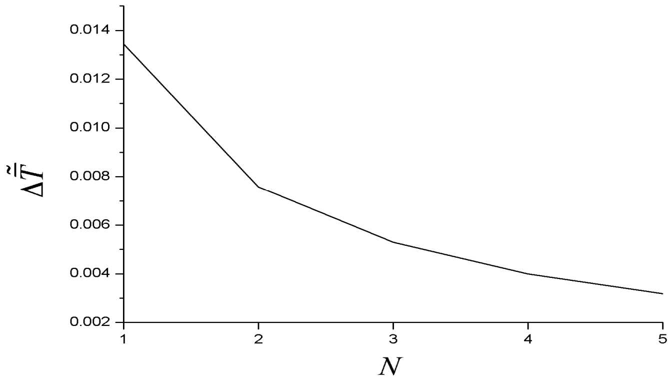

Figure 7. $\Delta\tilde{\tilde{T}}$ corresponding to $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ versus N

4.2 Maximization of $\tilde{G}/\Delta\tilde{\tilde{T}}$ at different $\tilde{V}$

$\tilde{G}/\Delta\tilde{\tilde{T}}$ versus $\tilde{R}_{\text{out}}$ at different $\tilde{V}$ is shown in Figure 8. There exists a $\tilde{R}_{\text{out},opt}$ that $\tilde{G}/\Delta\tilde{\tilde{T}}$ achieves its maximum and the performance of electromagnet achieves its best. The bigger $\tilde{V}$ is, the higher $\tilde{G}/\Delta\tilde{\tilde{T}}$ is, and the better the performance of the electromagnet is. Figure 9 shows that the $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ increases and approaches a constant value as $\tilde{V}$ increases. The corresponding $\tilde{R}_{\text{out},opt}$ and $\tilde{L}_{opt}$ versus $\tilde{V}$ are shown in Figure 10. When the performance of electromagnet achieves its maximum, the corresponding $\tilde{G}$ versus $\tilde{V}$ and $\Delta\tilde{\tilde{T}}$ versus $\tilde{V}$ are shown in Figures 11 and 12, respectively. As $\tilde{V}$ increases, the magnetic induction $\tilde{G}$ increases firstly and then decreases. $\Delta\tilde{\tilde{T}}$ decreases as $\tilde{V}$ increases. $\Delta\tilde{\tilde{T}}/\Delta\tilde{T}$ corresponding to different N versus $\tilde{L}$ and $\tilde{R}_{\text{out}}$ is shown in Figure 13, the variation of N , $\tilde{L}$ or $\tilde{R}_{\text{out}}$ has little impact on $\Delta\tilde{\tilde{T}}/\Delta\tilde{T}$, and $\Delta\tilde{\tilde{T}}$ versus $\Delta\tilde{T}$ keeps constant.

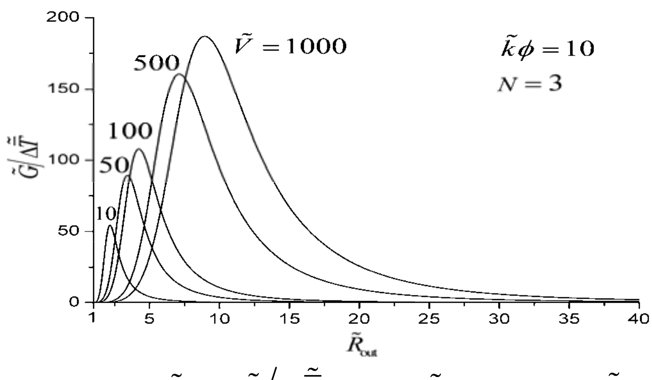

Figure 8. Effect of $\tilde{V}$ on $\tilde{G}/\Delta\tilde{\tilde{T}}$ versus $\tilde{R}_{\text{out}}$ with fixed $\tilde{k}\phi$ and N

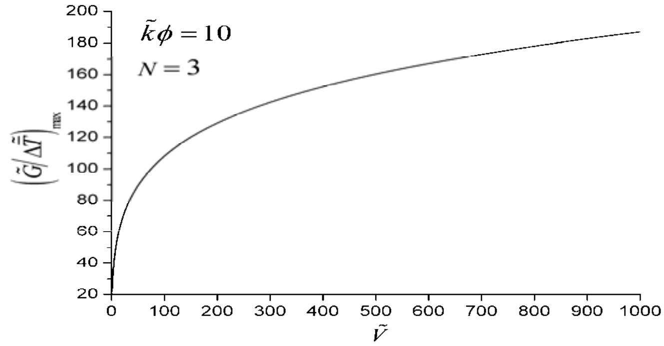

Figure 9. $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ versus $\tilde{V}$ with fixed $\tilde{k}\phi$ and N

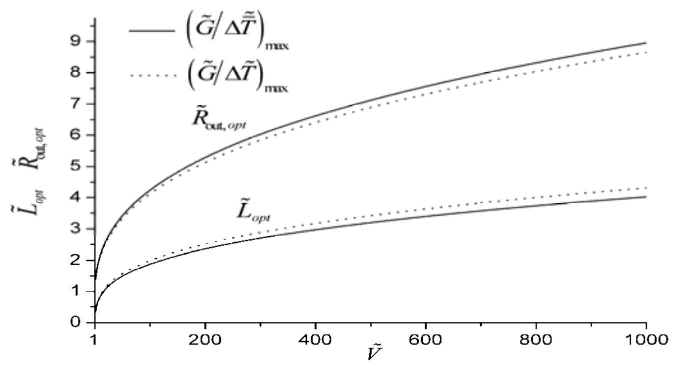

Figure 10. Comparisons between optimal geometries at $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ and $\left(\tilde{G}/\Delta\tilde{T}\right)_{\max}$

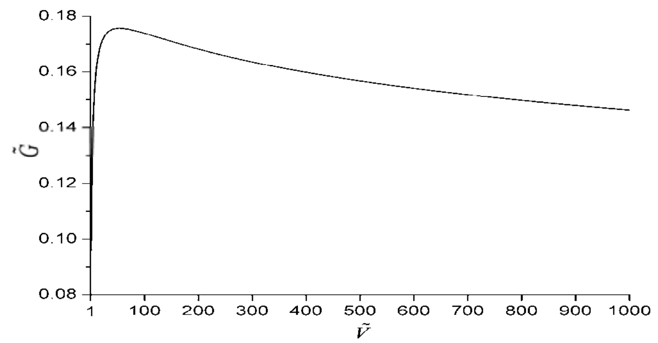

Figure 11. $\tilde{G}$ versus $\tilde{V}$ corresponding to $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$

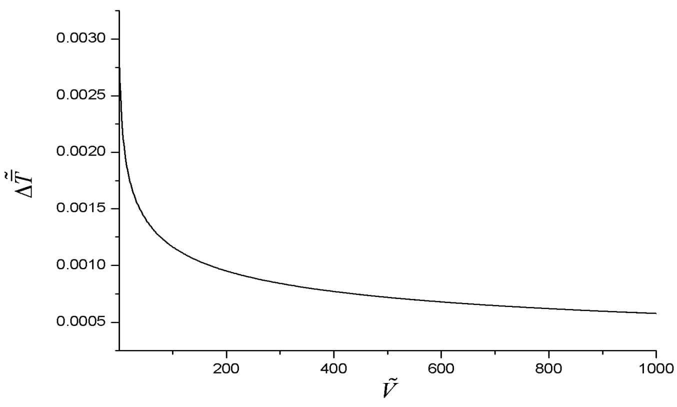

Figure 12. $\Delta\tilde{\tilde{T}}$ corresponding to $\left(\tilde{G}/\Delta\tilde{\tilde{T}}\right)_{\max}$ versus $\tilde{V}$

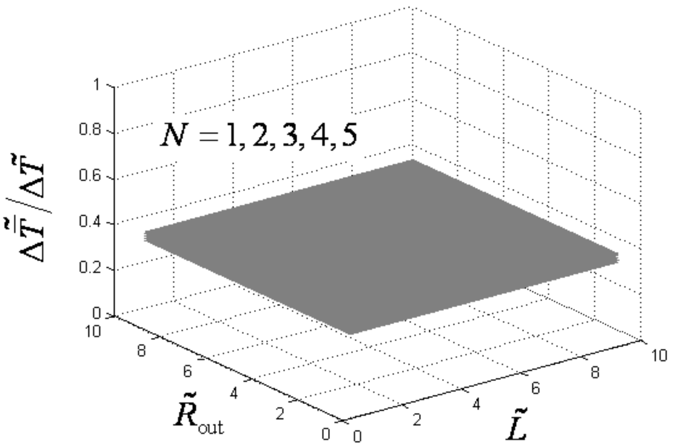

Figure 13. $\Delta\tilde{\tilde{T}}/\Delta\tilde{T}$ corresponding to different N versus $\tilde{L}$ and $\tilde{R}_{\text{out}}$

5. Conclusion

Considering that the performance of electromagnet requests low entransy dissipation rate and high magnetic induction, a complex-objective function of magnetic induction and entransy dissipation rate is provided. The optimization results show that the performance of electromagnet is improved as the number N of the high thermal conductivity cooling discs inserted increases. When $(\tilde{G}/\Delta\tilde{\tilde{T}})$ achieves its maximum $(\tilde{G}/\Delta\tilde{\tilde{T}})_{\max}$, the solenoid becomes longer and thinner as N increases. As N increases, the magnetic induction increases and the mean temperature difference decreases. $(\tilde{G}/\Delta\tilde{\tilde{T}})_{\max}$ also increases as $\tilde{V}$ increases, simultaneously, the magnetic induction increases firstly and then decreases, and the mean temperature difference decreases all along. The optimization with the complex-objective can lead to performance improvement of the electromagnet.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant Nos. 51176203, 51206184 and 51356001).

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