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Numerical studies on the inherent interrelationship between field synergy principle and entransy dissipation extreme principle for enhancing convective heat transfer

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A B S T R A C T

In 1998 Guo et al. integrated the boundary-layer energy equation along the thermal boundary layer thickness, and noted that at outside boundary the temperature gradient is zero and the convection term is actually the inner production of vector velocity and temperature gradient, they found that for a fixed flow rate and temperature difference, the smaller the intersection angle between velocity and temperature gradient the larger the heat transfer rate. This idea is called field synergy principle (FSP). Later it has been shown that FSP can unify all mechanisms for enhancing single phase heat transfer. In 2007 Guo and his co-workers proposed a new concept: entransy to describe the potential of a body to transfer thermal energy and the entransy dissipation extreme principle (EDEP). It is indicated that for any heat transfer process the entransy of the system is always dissipated, which can be regarded as the indication of the irreversibility of the transport process. For a heat transfer process with given boundary temperature condition the best one has the maximum entransy dissipation, while for that with given boundary heat flux condition the best one has minimum entransy dissipation. The combination of the two cases is called the entransy dissipation extremum principle.

The purpose of this paper is to reveal the inherent interrelationship between the ideas of field synergy principle and the entransy extremum principle. Numerical simulations are conducted for five examples of convective heat transfer. All the numerical results demonstrate the inherent consistency between FSP and EDEP.

1. Introduction to FSP

Although the basic principles of heat transfer theory have been built up at least for more than half-century, its development is still one of the hottest topics in the field of the applied thermal science. Among the three modes of heat transfer the focus of the present work is concentrated on the convective heat transfer. Generally speaking, at preliminary stage (i.e., approximately before 1960s), most studies focused on revealing the fundamental mechanism of convective heat transfer and establishing correlations between Nusselt number and Reynolds number, and there was almost no such a term as “heat transfer enhancement/ augmentation” in the open literature and textbooks [1–9]. Later, the energy crisis in 1970s broke this situation. The dilemma greatly shocked the global economy and forced people to reduce the excessive energy consumptions and efficiently utilize the available energy sources. It is estimated that among the all kinds of energy sources existing in the world, about 80% will go through the thermal energy form before they are transformed into electricity. Therefore thermal energy transformation or transition is a very important process in the energy utilization. The thermal energy transmission by convective heat transfer needs some power to drive the fluid. Thus seeking methods to enhance heat transfer in a certain process with minimal energy consumption is of significant importance in reducing energy consumption. Since then, heat transfer enhancement has become one of the hottest research subjects in the field of heat transfer. To the authors knowledge the terminology of Enhancement of Heat Transfer/Augmentation of Heat Transfer was first put forward in open literature by Bergles in [10]. After 1990s, the technology of heat transfer enhancement has evolved from the so-called second-generation technology to the third-generation technology [11–13] and significant achievements have been achieved. In 2002, the fourth-generation concept of heat transfer enhancement technology was proposed in [14].

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During the last few decades, great achievements on convective heat transfer enhancement have been obtained and various kinds of technologies have been adopted for single-phase convective heat transfer enhancement, i.e., (1) mixing the main flow and/or the flow in the wall region by using rough surface, insert, vortex generators, etc., (2) reducing the boundary layer thickness by using interrupted fins or jet impingement, etc., (3) creating velocity gradient at wall, etc. Many such techniques are presented in [15–17].

However, the essence of the convective heat transfer enhancement was still unclear in the nineties of the last century, even for the single phase convective heat transfer. Although some explanations can account for the mechanism of the heat transfer enhancement in some special cases, they was no unified principle or theory to explain the physical mechanism for the enhancement of single-phase convective heat transfer process till the end of the last century.

In 1998, Guo and his co-workers [18–21] proposed the concept of enhancing single-phase convective heat transfer for the parabolic fluid flow situation by transforming the convective term of the energy equation into the form of dot product of velocity vector and the temperature gradient, and integrating the energy equation over the thermal boundary layer. Consider a 2-D boundary-layer steady-state flow over a cold flat plate at zero incident angle the energy equation is as follows:

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) \tag{1}$$

The integration of Eq. (1) over the thermal boundary layer yields:

$$\int_0^{\delta_t}\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)dy=-\lambda\left.\frac{\partial T}{\partial y}\right|_w=q_w \tag{2}$$

That is:

$$\rho c_p\int_0^{\delta_t}(\vec{U}\cdot gradT)dy=-\lambda\left(\frac{\partial T}{\partial y}\right)_{y=0}=q_w \tag{3}$$

The product of the velocity vector and the temperature gradient can be given by

$$\overline{U}\cdot gradT=|\overline{U}|\cdot|gradT|\cos\theta \tag{4}$$

with θ denoting the intersection angle between the velocity vector and the temperature gradient.

From Eqs. (3) and (4) it can be seen that the convective heat transfer performance can be effectively improved by reducing the intersection angle between the velocity vector and the temperature gradient. According to the Webster Dictionary [22] "synergy" means combined or cooperative action or force. Hence this idea is called field synergy principle (FSP), and the intersection angle synergy angle. Later, Tao et al. [23,24] extended the FSP to the case of elliptic flow and tested its applicability via many numerical examples. Their work shows that the FSP gives a general mechanism for enhancing single phase convective heat transfer, and the three existing explanations mentioned above can be unified by FSP. In [25] Guo et al. further described the meanings of synergy. It is pointed out that the synergy between the velocity vector and the temperature gradient means: (a) the intersection angle between the velocity and the temperature gradient should be as small as possible; (b) the local values of the three scalar fields should all be simultaneously large; (c) the velocity and temperature profiles at each cross section should be as uniform as possible for internal flows. This is the complete understanding of the terminology "synergy". From then on, extensive works have been done to apply it for the development of heat transfer enhancement technology.

Intrinsically, the strength of the convective heat transfer relies on the synergy between the velocity and temperature fields. The question is how to characterize the synergy degree between two fields. The most useful application of the FSP is to reveal for the entire flow field where the synergy is bad and hence it is there enhancement technique should be adopted. Because enhancement technique usually will result in an increase in fluid pressure drop. Only those local areas in the flow domain where synergy are bad the adoption of enhancing technique may lead to increase heat transfer appreciably with a mild or small pressure drop increase. In this regard, the local synergy angle between velocity and the temperature gradient is the most suitable one.

The local synergy angle between the velocity vector and the temperature gradient is defined as

$$\theta=\cos^{-1}\left(\frac{U\cdot\nabla T}{|U||\nabla T|}\right) \tag{5}$$

With the local field synergy angle, many studies were conducted to obtain a general index to describe the field synergy degree in the entire flow system. The question is how to appropriately average the local synergy angle. Zhou [26] proposed five different ways for averaging synergy angles. Those are defined, respectively, by (1) simple arithmetic mean, (2) volume-weighted mean, (3) vector module-weighted mean, (4) vector dot product-weighted mean and (5) domain integration mean. It is found that except the simple arithmetic mean method, the rest are in accordance with each other qualitatively. For the case of air flowing across a certain finned tube, the variations of the mean synergy angles of different definitions with fluid velocity are plotted in Fig. 1. Clearly, there are no great qualitative differences between the variation trends of the different averaged field synergy angles. As it is the variation trend of field synergy angle that is used to guide practical problems, it is safe to adopt any one of them to qualitatively explain the reason/mechanism of the heat transfer enhancement. Usually, the average synergy angle based on the volume-weighted mean, and domain integration mean are employed, which can be written as

$$\text{Volume}-\text{weighted mean }\theta_m=\frac{\sum\theta_i dV_i}{\sum dV_i} \tag{6a}$$

$$\text{Domain integration mean }\theta_m=\arccos\frac{\sum|\vec{u}|\bullet|gradt|\bullet\cos\theta_i\bullet dV}{\sum|\vec{u}|\bullet|gradt|\bullet dV} \tag{6b}$$

It should be noted that the definition of Eq. (6b) is the most agreeable to the complete understanding of the concept of synergy described in [25].

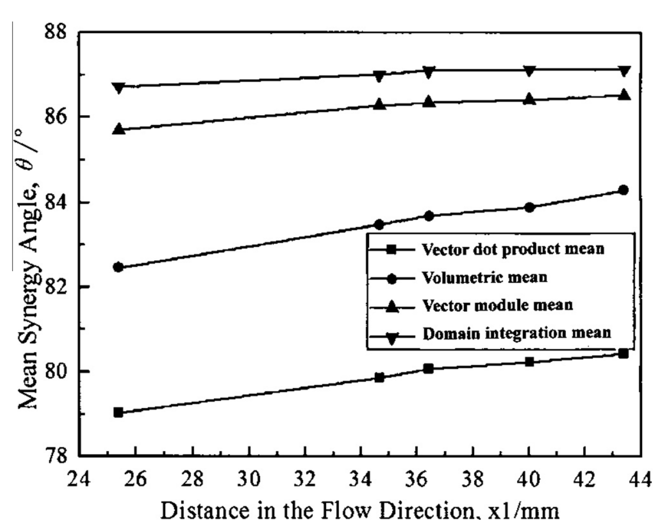

Fig. 1. Variations of the mean synergy angle with different definition.