International Journal of Thermal Sciences 80 (2014) 23–32

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Physical quantity synergy analysis and efficiency evaluation criterion of heat transfer enhancement

Lei Ma, Jie Yang, Wei Liu*, Xiaoyu Zhang

School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 5 May 2013
Received in revised form
5 October 2013
Accepted 27 January 2014
Available online 4 March 2014

Keywords:
Multi-fields synergy
Efficiency evaluation criterion
Convective heat transfer

ABSTRACT

On the basis of the core-flow heat transfer enhancement and field synergy principle, the difference between fluid-oriented and surface-oriented heat transfer enhancement methods is performed. The physical nature of heat transfer enhancement and friction reduction is illustrated through revealing the synergy principle of heat transfer and friction characteristics of physical quantity and describing the internal relations of velocity and temperature fields as well as velocity and pressure fields. The efficiency evaluation criterion (*EEC*) and the efficiency evaluation plot are proposed to analyze and evaluate heat transfer enhancement techniques corresponding to the different regions in the efficiency evaluation plot. Region I represents the heat transfer enhancement ratio is larger than the pumping power increase ratio and region II represents the heat transfer enhancement ratio is less than the pumping power increase ratio in comparison with a bare tube. 3-D numerical simulations of several inserts in tube are provided to verify multi-fields synergy principle of convective heat transfer and efficiency evaluation plot is carried out to demonstrate the characteristics of enhancement tubes.

1. Introduction

Heat exchangers have been an active subject for applications in engineering field and investigations in academic field in the past several decades. Researches for heat exchangers are aimed at increasing the heat transfer coefficient and decreasing pressure penalty. However, the improved heat transfer techniques prefer to bring heat transfer intensification with the presence of power consumption augmentation in most cases.

There are three aspects on the research for heat transfer enhancement, which are theoretical, numerical and experimental. Theoretically, Bergles [1] divided heat transfer technology into four generations, the first generation of which is bare tube (no fins), the second of which is plain, the third of which is longitudinal vortex generators on fins and the fourth of which is fins with vortex generators subject to electrostatic fields. Specifically speaking, decreasing the thermal boundary layer thickness, extending heat transfer surface area and altering thermal physical property of heat transfer surface are popular ways for heat transfer enhancement [2], which are defined as the boundary layer heat transfer enhancement as the enhanced ways are based on surface [1]. Bejan [3] divided fluid flow into two parts: the boundary flow and the core flow. For the boundary flow heat transfer enhancement, it is common that the ratio of pressure drop increase is always larger than the ratio of heat transfer enhancement. Liu [4–6] analyzed the difference between the boundary flow and the core flow and proposed heat transfer enhancement in the core flow, which is mainly expressed as (1) strengthening temperature uniformity in the core flow; (2) increasing fluid disturbance in the core flow; (3) reducing surface areas of heat transfer elements in the core flow; (4) decreasing fluid disturbance in the boundary flow. Webb [2] proposed three principles of heat transfer enhancement evaluation, which are (1) the size and surface area of the enhanced heat exchangers for the equal pumping power, flow rate and heat transfer rate; (2) the heat transfer rate of the enhanced heat exchangers for the equal size, flow rate and pressure drop; (3) the pressure drop of the enhanced heat exchangers for the equal size, heat transfer rate and fluid rate in comparison with the regular heat exchangers. Guo [7,8] and his co-workers afresh surveyed the physical mechanism of convective heat transfer and proposed a novel concept named field synergy principle for enhancing heat transfer derived from analysis of laminar flow in 2-D flat plate, considering the degree of convective heat transfer is related to the reduction of the intersection angle of velocity and temperature field. According to the field synergy principle, the better the synergy between velocity field and temperature field is, the higher the heat transfer

* Corresponding author. Tel.: +86 27 87542618; fax: +86 27 87540724.
E-mail address: w_liu@hust.edu.cn (W. Liu).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.01.021
1290-0729/

intensification will be under the same boundary conditions of velocity and temperature. As an extension, Tao [9] demonstrated the three mechanisms, i.e. the decreasing the thermal boundary layer, the increasing of the flow interruption and the increasing of the velocity gradient near a heat transfer wall, all lead to the reduction of the intersection angle between the velocity and the temperature field. Numerically and experimentally, lots of research [10–15] such as square ducts, single-phase flow, elliptic tubes, wavy fin heat exchangers with elliptic tubes and fin-and-oval-tube heat exchanger with longitudinal vortex generators is provided according to the theoretical guide. Liu [16–18] developed the principle of synergy and proposed the principle of multi-fields physical quantity synergy for convective heat transfer, introducing more synergy angles on the basis of velocity, temperature and pressure fields and revealing the fundamental nature of heat transfer enhancement and pressure drop reduction. Bejan [19–21] analyzed the entropy generation of heat transfer process based on the second law of thermodynamics and proposed performance evaluation of heat transfer process. It is understood that the detailed methods of heat transfer enhancement can be easily invented once the theoretical research such as enhancement mechanism and evaluation criteria are established. Therefore, the focus of this paper is theoretical analysis with numerical verifications illustrated as follow.

The paper established synergy relation of heat transfer and friction characteristics by analyzing multi-fields for convective heat transfer in tube, based on the core flow heat transfer enhancement and principle of field synergy. The comprehensive value of *EEC* and an evaluation efficiency plot are introduced to evaluate the enhanced techniques. Numerical computations of additives in tube are provided to validate synergy principle and comprehensive efficiency evaluation plot.

2. Physical quantity synergy for convective heat transfer in laminar

The enhancement of convective heat transfer is based on increasing heat transfer coefficient as well as decreasing pressure penalty. For the present enhanced techniques, it is a common knowledge that ratio of flow resistance increment is often larger than the ratio of heat transfer enhancement. Thus it is of considerable significance to enhance heat transfer without much pressure drop augmentation. Based on the internal relations of velocity, temperature and pressure fields, synergy principle of multi-fields for convective heat transfer in laminar flow in tube is introduced.

Refs. [7,8,16–18] proposed the synergy between velocity gradient and temperature gradient and described a dot product of the dimensionless velocity and temperature gradient, which is expressed as:

$$\overline{\boldsymbol{U}}\cdot\nabla\overline{T} = \left|\overline{\boldsymbol{U}}\right|\left|\nabla\overline{T}\right|\cos\beta \tag{1}$$

where $\overline{\boldsymbol{U}}$ and $\nabla\overline{T}$ denote the non-dimensional numbers and definition can be seen in Ref. [17].

For a fixed flow rate and temperature difference in a channel, the smaller intersection angle β between $\overline{\boldsymbol{U}}$ and $\nabla\overline{T}$ is, the larger the dot product $\overline{\boldsymbol{U}}\cdot\nabla\overline{T}$ will be; and the larger Nu is, the more active the convective heat transfer between fluid and a solid wall will be.

Refs. [17,18] proposed the synergy between velocity and pressure gradient, and expressed the synergy relation between velocity vector $\boldsymbol{U}$ and pressure gradient ∇p as:

$$\boldsymbol{U}\cdot(-\nabla p) = |\boldsymbol{U}||-\nabla p|\cos\theta \tag{2}$$

For a fixed flow rate and pressure difference in a channel, the smaller intersection angle θ between $\boldsymbol{U}$ and $-\nabla p$ is, the smaller $|\boldsymbol{U}||-\nabla p|$ will be under fixed $\boldsymbol{U}\cdot(-\nabla p)$. That means less power consumption is employed in the channel.

Based on the analysis of multi-fields synergy for convective heat transfer, two synergy angles of β and θ are introduced to reflect the heat transfer and power consumption characteristics of fluid, revealing the physical nature of heat transfer augmentation and pressure penalty reduction and showing a significance on the design and optimization of heat transfer units and heat exchangers.

3. Heat transfer enhancement in the core flow of a tube

Based on the nature of heat transfer enhancement, Liu [4–6] proposed a principle of heat transfer in the core flow, which is interpolating various heat transfer elements with clearance to the tube wall and enhancing heat transfer in the core flow region, compared with the boundary heat transfer. There are two basic rules for principle of heat transfer enhancement in the core flow, one of which is to improve temperature uniformity and the other of which is to reduce pressure penalty. For the purpose of heat transfer enhancement, the rule of improving temperature uniformity aims at (1) disturbing fluid in the core flow, (2) improving temperature uniformity in the core flow, (3) forming thinner thermal boundary layer near the tube wall, (4) increasing the temperature gradient of thermal boundary layer. Meanwhile, for the purpose of power consumption reduction, the rule of reducing pressure penalty aims at (1) reducing area of additives in the core flow, (2) avoiding disturbance of fluid near tube.

For the boundary flow heat transfer enhancement, due to the elements attached the tube conducting heat flux between fluid to the tube wall, convective heat transfer coefficient between fluid and additives surface can be defined. Whereas, for the core flow heat transfer enhancement, the elements enhancing heat transfer fail to conduct heat flux to tube wall due to the clearance and thus convective heat transfer coefficient between fluid and additives surface does not exist.

In comparison with boundary flow heat transfer, enhancing heat transfer and reducing pressure penalty can be achieved at the same time in the core flow heat transfer, resulting from the fact that a wider region can be taken into account in core flow region to reduce pressure drop and intensify heat transfer by decreasing axial up-coming area and dispersing elements to intensify disturbance to get lower pressure penalty and more vortexes generated in core flow region to get higher convective heat transfer coefficient. Moreover, pressure drop can also be significantly reduced by lower disturbance in boundary layer and less area of elements disturbing fluid.

The above elements of heat transfer enhancement inserted in the core flow of a tube can be divided into two types, one of which is applied to uniform the temperature field, and the other of which is employed to disturb the fluid flow. The elements applied to uniform temperature field, such as porous medium, enhance heat transfer by improving the overall thermal conductivity in the core flow. While the elements employed to disturb the fluid flow, such as twisted tapes and helical screw-tapes, make heat transfer augmentation by disturbing flow and generating vortexes in tube. Synergy angles β and θ vary in the core flow region due to these additives. In this paper, all the following simulations are based on core flow region.

4. Efficiency evaluation criterion and efficiency evaluation plot

He et al. [22] proposed a performance evaluation plot which taking friction factor increase f/f_0 and heat transfer enhancement Nu/Nu_0 as abscissa and ordinate, respectively, and divided the