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Entropy production and field synergy principle in turbulent vortical flows

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ABSTRACT

The heat transfer in turbulent vortical flows is investigated by three different physical approaches. Vortical structures are generated by inclined baffles in a turbulent pipe flow, of three different configurations. In the first, the vortex generators are aligned and inclined in the flow direction (called the *reference geometry*); in the second, a periodic 45° rotation is applied to the tab arrays (*alternating geometry*); the third is the reference geometry used in the direction opposite to the flow (*reversed geometry*). The effect of the flow structure on the temperature distribution in these different configurations is analyzed. The conventional approach based on heat-transfer analysis using the Nusselt number and the enhancement factor is used to determine the efficiency of these geometries relative to other heat exchangers in the literature.

The effect of vorticity on the Nusselt number is clearly demonstrated, and so as to highlight the respective roles of the coherent structures and the turbulence, a new parameter is defined as the ratio of the *vortex circulation* to the *turbulent viscosity*. The relative contribution of the radial convection to heat transfer appears to increase with Reynolds number. The effect of mixing performance on the temperature distribution is investigated by the *field synergy* method. A global parameter, namely the intersection angle between the velocity and temperature gradient, is defined in order to compare performances. Finally, an analysis of energetic efficiency by entropy production, involving both heat transfer and pressure losses, is carried out to determine the overall performance of the heat exchangers.

All these approaches lead to the same conclusion: that the reversed geometry presents the best heat transfer coefficient and the best energetic efficiency. The reference geometry shows the worst performance, and the alternating array has intermediate performance.

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1. Introduction

Forced heat transfer in the turbulent regime is generally controlled by the convective motion of large-scale eddies that appear essentially as transverse and longitudinal vorticity [1,2]. These embedded flow structures, which can be generated by shear instabilities or pressure gradients, play a crucial role in the heat- and mass-transfer mechanisms. The pattern of these vortices in the flow has a decisive impact on the hydrodynamic and thermal performance of thermal devices used in industrial applications [1–11]. A physical understanding of this impact is a fundamental issue in optimizing the energetic efficiency of multifunctional heat exchangers-reactors (MHER) for Green Process Engineering [12].

Several approaches have been used to investigate the heat-transfer mechanisms in the presence of longitudinal vortices in turbulent flow: global approaches using the Nusselt number and an enhancement factor, and also more advanced approaches involving i) the vortex circulation, ii) the field synergy principle, iii) entropy production, as described below. In the present work, vortices are produced by using three different vortex generator positions in a turbulent pipe flow: the vortex generators are aligned, alternating, or reversed. The global approach is based on the determination of the Nusselt number, which characterizes the convective heat transfer in the flow, and the friction factor, which determines pressure losses. The enhancement factor is defined as the ratio of the convective heat transfer coefficient of the straight-pipe flow over that of the current geometry [13,14]. This parameter allows

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