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An experimental analysis of the flow pattern in heat exchangers with an egg carton configuration (parallel, convergent and divergent cases)

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ABSTRACT

An experimental analysis about the flow patterns that appear in the channel formed between two corrugated plates with an egg carton configuration is reported. The types of flow instabilities caused by the corrugated plates are identified and described by means of flow visualization experiments, and photographic sequences illustrate the flow features present for each case. The influence on flow instabilities of Reynolds number, phase angle, convergence/divergence angle and spacing between corrugated plates is investigated. The corrugated plates are set divergent and convergent in order to investigate if recirculations are broken by chaotic advection. The improvement of heat transfer in the laminar regime has become an essential task in many applications and therefore the experiments are conducted in this regime.

The corrugated plates geometry provides two main advantages over the conventional plane plates: the recirculation zones observed in the longitudinal direction and the three-dimensionality of the flow, i.e. the recirculations reduce the thermal resistances while the three-dimensionality of flow generates a better mixing and a more uniform temperature distribution.

This experimental study contributes to the general knowledge on the subject being the first that addresses the analysis of convergent and divergent egg carton plates. It is expected that the results presented here will shed some light as to advantageously use these geometries in the near-future heat exchangers. (Because of the improve chaotic mixing in divergent corrugated plates, this configuration may be a good option to improve heat exchangers performance, because a better mixing is always related to the presence of core fluid near exchange surfaces, and consequently an increase in temperature gradients and heat transfer.)

1. Introduction

Obtaining good fluid mixing, reduction of heat transfer resistances, and minimum pressure drops are very important factors in the design of heat transfer devices. Good mixing may be obtained by operating heat exchangers in the turbulent regime, although the turbulent regime implies high pressure drop. Operating heat exchangers in the turbulent regime increases the pumping costs, which is a limiting factor in some applications, such as compact heat exchangers and heat transfer of high viscosity fluids. Additionally, in recent times, heat transfer under laminar flow conditions has assumed relevance in applications such as bioreactors and blood oxygenators (Nishimura and Kawamura, 1995).

Several techniques have been used to enhance heat transfer in plate heat exchangers (Braun et al., 1999; Herman and Kang, 2002; Lyman et al., 2002), one of the most frequent one uses wavy plates instead of flat plates. Many investigations (most of them numerical) have demonstrated that using sinusoidal plates instead of flat plates improves the heat transfer without a large increase in pressure drop (Gschwind et al., 1995; Islamoglu and Parmaksizoglu, 2004; Jang and Chen, 1997; Mahmud et al., 2002; Rush et al., 1999; Sawyers et al., 1998; Wang and Chen, 2002; Zhang et al., 2004).

Some researchers have proposed to improve laminar mixing in those applications by means of chaotic advection. When the fluid presents pathlines that do not conform to the laminar regime, such fluid presents chaotic advection. Chaotic particle paths can be found in two-dimensional time-depending flows as well as in three-dimensional flows. There are two ways to promote chaotic mixing in two-dimensional systems with deterministic particle paths. One of those techniques consists of perturbing the flow by means of an external periodic force that creates transient flow, the other one consist of generating a three-dimensional flow component. Chaotic mixing can be generated in ducts, if the duct geometry is periodically perturbed in the downstream direction. Clear examples of how to improve heat transfer by means of

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Nomenclature

A	dimensional amplitude, cm	ϕ	phase angle
h	distance between upper wall and channel centerline, cm	β	dimensionless amplitude
H_{avg}	average channel width, cm	λ	dimensionless wavelength
V_{in}	average inlet channel velocity, cm s^{-1}	Λ	dimensional wavelength, cm
Re	Reynolds number, dimensionless	ν	kinematic viscosity, $cm^2\,s^{-1}$
x, y, z	cartesian coordinate system		
		Subscripts	
Greek symbols		x, z	x and z directions
α	convergence/divergence angle		

chaotic advection are available in the literature (Chagny et al., 2000; Chang and Sen, 1994; Froncioni et al., 1997; Galaktionov et al., 2002; Howes and Shardlow, 1997; Jones, 1994; Lefevre et al., 2003; Lemenand and Peerhossaini, 2002; Liu et al., 1994; Mokrani et al., 1997; Raynal and Gence, 1997; Sawyers et al., 1998; Southerland et al., 1994; Tabor and Klapper, 1994). As an example, Mokrani et al. (1997) experimentally investigated chaotic advection as a means to improve heat exchanger performance. They compared the behavior of two shell-and-tube heat exchangers: a helical-coil heat exchanger and a twisted pipe-coil heat exchanger (chaotic heat exchanger). The chaotic heat exchanger was assembled with bends and straight tubes. The bends were set in such a way that neighboring bends were orthogonal in order to generate three-dimensional flow as well as chaotic behavior. These authors performed experiments for Reynolds numbers between 60 and 200. They demonstrated that the temperature profile of the chaotic heat exchanger is better distributed than that of the helical-coil heat exchanger. This behavior is caused by the chaotic particle paths that improve the mixing in the chaotic heat exchanger. Finally, these authors determined that the relative enhancement in performance of the chaotic heat exchanger, in comparison with the helical-coil heat exchanger, was of the order of 13–28%.

Another clear example that shows how to generate chaotic advection is the research performed by Liu et al. (1994). They studied mixing characteristics in chaotic periodic flows as well as in chaotic non-periodic flows, numerically determining the position of particles in a two-dimensional rectangular cavity with two moving walls. They induced transient flow and chaotic paths by displacing periodically or aperiodically the moving walls, finding that the mixing distribution in aperiodic flows is better than in periodic flows (thus the heat transfer is better in aperiodic flows).

On the other hand, some non-conventional ways have been introduced to enhance the behavior in plate heat exchangers, and one of the most important ones is wavy plates instead of flat plates. The fluid convective thermal resistance is reduced by means of this technique. Some investigations have demonstrated that using sinusoidal plates instead of flat plates improves the heat transfer without a great increase in the pressure drop (Gschwind et al., 1995; Islamoglu and Parmaksizoglu, 2004; Jang and Chen, 1997; Mahmud et al., 2002; Rush et al., 1999; Wang and Chen, 2002; Zhang et al., 2004).

Recently, the flow pattern in plates with corrugations in the transversal and parallel directions to the flow (*egg carton configuration*) has been investigated by means of an analytic-numerical technique (Sawyers et al., 1998). This kind of investigation is one of the most innovative in relation to corrugated plates as a means to improve the heat transfer, and it could provide state of the art knowledge about the existence of chaotic particle paths in egg carton channels. Sawyers et al. (1998) investigated the flow pattern between two corrugated plates with the egg carton configuration and a 180° phase angle. They determined the flow characteristics in steady state, paying special attention to the way to improve the heat transfer by generating chaotic particle paths in three-dimensional steady flows. For zero angle of attack, in symmetry planes, it was determined that the flow pattern is similar to the flow pattern in sinusoidal corrugated plates. For small flow angles ($0° < \alpha \leqslant 2.37°$), particles leave recirculation zones, and incorporate to the main core flow, allowing an enhancement in the heat transfer, compared to recirculation zones in flows with zero angle of attack. When the angle of attack is large ($\alpha > 2.37$), the recirculation region is destroyed by the transverse flow, and the heat transfer diminishes.

Steady state is assumed in most of the analytical and numerical investigations in relation to corrugated sinusoidal plates, however, some experimental evidence (Stone and Vanka, 1999) has demonstrated that steady state is only reached for very small Reynolds numbers. As the Reynolds number is increased, the flow close to the corrugated plate channel outlet becomes unsteady, and the instabilities approach the corrugated plate channel inlet. At very high Reynolds numbers, instabilities appear in the entire channel with the exception of the first wave (not at the channel inlet, but downstream from it), which shows steady state at very high Reynolds numbers. Sawyers et al. (1998) considered steady flow in their investigation of flow in egg carton channels.

The present experimental investigation studies the flow pattern in corrugated plates with the egg carton configuration. The types of instabilities as well as their relationship to the Reynolds number, the phase angle, convergence/divergence angle, and the spacing between corrugated plates is studied. Additionally, it is investigated if recirculation zones are broken by chaotic advection when the corrugated plates are set divergent or convergent. Apart from this study being an experimental one, which in itself contributes to the general knowledge on the subject, another important novelty is to include the analysis for convergent and for divergent egg carton plates, which has not been yet reported in the technical literature has undertaken. It is expected that the results presented here will shed some light as to advantageously use these geometries in the design of future heat exchangers.

2. Experimental methodology

Experimental flow visualization methods have been used in order to investigate the flow pattern in a wide array of very important problems in fluid mechanics (DeJong and Jacobi, 2003; El-Sayed et al., 2002; Lin et al., 2002; Romero-Méndez et al., 2000; Rush et al., 1999). For example, Rush et al. (1999) successfully used flow visualization by injecting dye to establish the flow pattern characteristics that exist between two finite sinusoidal corrugated plates. The flow visualization methods that use water as the working fluid are very appropriate for visualizing the flow pattern between two corrugated plates in plate heat exchangers. Using water as the working fluid enables one to establish appropriate