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Integration of constructal distributors to a mini crossflow heat exchanger and their assembly configuration optimization

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Abstract

In this paper, the idea of coupling constructal distributors/collectors with a mini crossflow heat exchanger (MCHE) to solve the problem of flow maldistribution is presented. After a brief description of the design and scaling laws of the constructal distributor, experimental and simulation results have been discussed to investigate relations among flow distribution, heat transfer and pressure drop. It is shown that the introduction of constructal distributors and/or collectors could improve the quality of fluid distribution and consequently lead to heat transfer intensification of the MCHE, but it also results in higher pressure drops. Different assembly configurations involving distributor, heat exchanger and collector have also been compared. The configuration where the inlet is equipped with a conventional pyramid distributor and the outlet is equipped with a constructal collector (Apec) shows a relatively higher thermal performance as well as low pressure drops in our cases considered.

Keywords: Flow maldistribution; Constructal distributor; Mini crossflow heat exchanger (MCHE); Thermal performance; Pressure drop; Assembly configuration

1. Introduction

Heat exchangers, as typical process and chemical engineering units, are widely used in different aspects of industry. Nowadays, the demand for highly efficient heat exchangers such as compact heat exchangers has started increasing as a result of the diminishing world energy resources and increasing energy cost, which then stimulates the diversification of heat transfer intensification methods. However, a large part of these methods, either active or passive, is restricted to create extended useful heat transfer surfaces or to generate turbulence flow to increase the overall heat transfer coefficient. The deterioration in the performance of heat exchangers due to *flow maldistribution* should also be an important issue. In most design of heat exchangers, it is assumed that the flow is uniformly distributed over different channels or tubes, but under operating condition in real-world engineering, this assumption is questionable. A lot of related research works (Fleming, 1967; Chiou, 1978, 1980; Lalot et al., 1999; Ranganayakulu and Seetharamu, 1999a,b; Bobbili et al., 2002, 2006; Yuan, 2003; Jiao et al., 2003; Wen and Li, 2004; Jiao and Baek, 2005; Srihari et al., 2005) have proved that flow maldistribution reduces significantly the idealized heat exchanger performance especially in mini-scale heat exchangers and finding effective methods to solve this problem is a real challenge faced by researchers and engineers.

Besides the passage-to-passage maldistribution (Mueller and Chiou, 1988) which occurs within highly compact heat exchanger because of its manufacturing tolerances, fouling, condensable impurities, etc., more and more studies are focused on decreasing the gross maldistribution, which is mainly associated with improper design of distributor and/or collector configuration. Dispersion models have been proposed to describe the effect of flow maldistribution in shell-and-tube heat exchangers (Xuan and Roetzel, 1993; Roetzel and Ranong, 1999; Sahoo and Roetzel, 2002), finned tube heat exchangers (Aganda et al., 2000), plate heat exchangers (Roetzel and Das, 1995;

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Luo and Roetzel, 2001; Gut et al., 2004; Srihari et al., 2005), other cross-flow-type heat exchangers (Luo and Roetzel, 1998; Ranganayakulu and Seetharamu, 1999a; Lalot et al., 1999), etc. Various methods have been suggested in order to obtain a uniform inlet flow distribution. Some of these consists in adding "packings" that are random at small scales, but regular at the larger scales, such as a uniformly perforated grid (Lalot et al., 1999), a baffle (Wen and Li, 2004; Wen et al., 2006) or a second header (Jiao et al., 2003), resulting in a higher pressure drop and flow dispersion that are undesirable from the engineering point of view. Others include modifying the corrugation angles or geometrical dimension of the distributor (Lalot et al., 1999; Jiao and Baek, 2005; Bobbili et al., 2006) to improve the quality of flow distribution.

In fact, properties expected from a "good" distributor are equidistribution of the flow rate (uniform irrigation), minimal dispersion, minimal void volume and minimal pressure drop, leading necessarily to some compromise. This problem cannot be solved by conventional ways but may be approached using multi-scale optimization methodology such as the so-called "constructal approach", developed by Bejan and his co-workers from 1996 on, a quite general theory of multi-scale shapes and structures in nature and engineering (Bejan, 1997; Bejan and Tondeur, 1998). Details of the constructal approach may be found in Bejan (2000a) and in the book "Shape and Structure: from Engineering to Nature" (Bejan, 2000b). In "constructal" terms, the distributor or collector problem is topologically one of the connections between a point and a surface. The "point" is here the single inlet tube or pore, and the surface is the domain that must be fed by the distributed flow. The architecture for multi-objective systems that optimally distributes dissipation in time, space, scales and structure could be generated using constructal approach under specified constraints and duties (Luo et al., 2006).

The main objective of this paper is to present the idea of coupling constructal distributors/collectors with a heat exchanger to improve its thermal performance by solving the flow maldistribution problem. This work starts from the earlier work of Tondeur and Luo (2004) and Luo and Tondeur (2005a,b). Novel constructal distributors were designed and optimized by constructal approach and integrated to a MCHE. We first attempt to characterize distributors per se, that is, independently of the operation to which it will be attached. Then, numerical and experimental results are discussed in order to investigate the effect of constructal distributor/collector on the fluid equidistribution in the core of the MCHE, as well as its thermal performance and pressure drop. Clearly, there cannot be a unique correspondence between the global flux transferred and the quality of flow distribution, but a significant correlation should be possible between the effect of operating parameters (flow rates and temperatures) on the flux transferred on one hand, and an overall characteristic of the flow distribution on the other hand, a relation between variances for example. The parameters of useful pressure drop and lost pressure drop are defined to establish the relationships between the location of constructal component and the effect of flow equidistribution, and to the optimization of distributor/collector and heat exchanger assembly configuration. Finally, conclusions and future work are summarized.

2. Branched fluid distributor: design and scaling laws

Let us first describe the constructal distributor of Fig. 1. Branched distributor based on a so-called "dichotomic tree" and optimized by constructal approach was designed and manufactured by laser polymerization stereolithography (André and Corbel, 1994). The structure of this distributor is determined by an optimization criterion that specifies the total flow rate and accounts for both viscous dissipation and total pore volume. The design guidelines and detail optimization procedure by constructal approach could be found in Tondeur and Luo (2004) and Luo and Tondeur (2005a), and it will be instructive to briefly restate key scaling laws and some useful conclusions already arrived.

The pore space of the distributor has the structure of a sequence of eight generations of T- or Y-bifurcations or divisions. It has a branching logic in which every channel is divided into two smaller branches; the number of the smallest channels thus generated is 2^m where m is the number of levels of branching, or "generations". The number of channels that such a distributor can feed is therefore a power of 2 as $m = 0$ for the inlet channel. Since there are eight generations of bifurcations, there are $2^8 = 256$ final outlet channels.

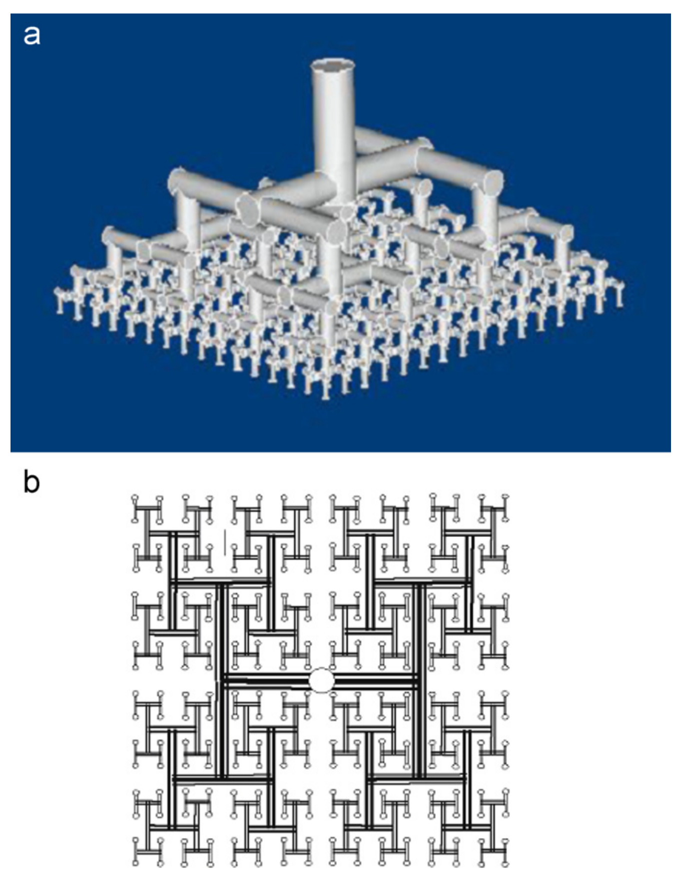

Fig. 1. Binary-branched fluid distributor. (a) Pore structure; (b) projection of pore network on base plane.