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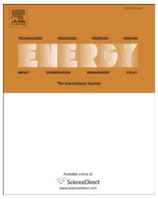

Multi-channel heat exchanger-reactor using arborescent distributors: A characterization study of fluid distribution, heat exchange performance and exothermic reaction

Xiaofeng Guo[a,b,1], Yilin Fan[a], Lingai Luo[a,*]

[a] Laboratoire de Thermocinétique, UMR CNRS 6607, Polytech'Nantes – Université de Nantes, La Chantrerie, Rue Christian Pauc, BP 50609, 44306 Nantes Cedex 03, France

[b] Laboratoire Optimisation de la Conception et Ingénierie de l'Environnement – LOCIE CNRS UMR5271, Université de Savoie, Campus Scientifique, Savoie Technolac, 73376 Le Bourget du Lac Cedex, France

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ABSTRACT

A multi-functional heat exchanger-reactor comprising arborescent (tree-like) distributors and collector, 16 mini-channels in parallel and T-mixers is introduced in this paper. Flow distribution property, pressure drop and heat exchange performance of proposed heat exchanger-reactor are tested and discussed. Firstly, flow distribution uniformity is characterized by CFD simulation and then qualitatively confirmed by visualization experiment. Results show that for total flowrates ranging from 5 mL s^{-1} to 20 mL s^{-1}, good distribution uniformity is obtained, with maximum flowrate deviation less than 10%. Then, experiments of heat exchange between hot and cold water are carried out. High values of overall heat transfer coefficient ranging from 2000 to 5000 W m^{-2} $°C^{-1}$ are obtained under our working conditions. The volumetric heat exchange capability (UA/V) is found to be around 200 kW m^{-3} $°C^{-1}$, showing a high heat exchange capability with compact design. The roles of end-effect and non-established flow are discussed and are supposed to be responsible for efficient heat transfer. Finally a typical fast exothermic reaction, neutralization between acid and basic solutions, is carried out to test the thermal control capability of the studied heat exchanger-reactor. Results indicate that isothermal condition could be realized by circulating appropriate flowrate of coolant through the heat exchanger.

The design of heat exchanger-reactor with arborescent distributor and collector makes possible the application of multi-channel systems. This paper introduces systematically the successful integration of heat exchanger-reactor and its performance evaluation.

1. Introduction

Heat exchanger usually appears in typical energy systems relating energy production, transportation, storage and conversions [1,2]. These systems are not intended merely to heat exchange but involve other processes and functions. Integration of heat exchanger with several system components, i.e. multifunctional devices, may be interesting in that energy consumption might be reduced and the system performance may be raised.

An example in the chemical engineering would be the heat exchanger-reactor integration. According to a study of ADEME (French Agency of Environment and Energy Management), energy consumption in a chemical plant contributes in average 61.7% of the final price of products [3]. Among different energy consumptions, thermal energy is the main source that guarantees proper control and management of process conditions. Usually this thermal condition is provided by circulating utility fluid. In low temperature conditions liquids are used as utility fluid while in higher temperature conditions (>100 °C) like in petrochemical processing, pressurised steam is served as the medium [4]. A better temperature control with reduced temperature difference between the utility fluid and process fluid is usually beneficial, regarding both process integration improvement [4] and exergy efficiency [5]. In particular, as studied by Cheng [6], entropy resistance should be minimized in

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[*] Corresponding author. Tel.: +33 2 40 68 31 67; fax: +33 2 40 68 31 41.
E-mail addresses: xiaofeng.guo@esiee.fr (X. Guo), yilin.fan@univ-nantes.fr (Y. Fan), lingai.luo@univ-nantes.fr (L. Luo).

[1] Present address: ESIEE Paris, Department SEN, Cité Descartes – 2 bd Blaise Pascal BP 99, 93162 Noisy Le Grand Cedex, France.

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Nomenclature

Notations

A	heat transfer surface area (m^2)
C	concentration (mol L^{-1})
c_p	fluid heat capacity (J g^{-1} °C^{-1})
d_i	tube internal diameter (m)
d_o	tube external diameter (m)
D_{ch}	flowrate deviation (%), defined by Eq. (1)
F	correction factor
f_{ch}	mass flowrate in a channel (kg s^{-1})
f_{av}	calculated average mass flow in each channel (kg s^{-1})
h	convective heat exchange coefficient (W m^{-2} °C^{-1})
ΔH	standard molar enthalpy of formation (kJ mol^{-1})
ΔH_r	reaction enthalpy (kJ mol^{-1})
$\dot{m}$	total mass flowrate (kg s^{-1})
Nu	Nusselt number
Pr	Prandtl number of fluid
Q	volume flowrate (mL s^{-1})
Re	Reynolds number
Φ	heat exchange rate (W)
λ	thermal conductivity of fluid (W m^{-1} °C^{-1})
λ_{cc}	thermal conductivity of Cobalt Chrome (W m^{-1} °C^{-1})
T	temperature (°C)
U	overall heat exchange coefficient (W m^{-2} °C^{-1})
V	total volume of reactor (m^3)
ΔP	pressure loss (bar)
ρ	density (kg m^{-3})

Indices

h, c	hot or cold side
i, o	inlet or outlet of fluid
effective	effective transfer area considering end effects
process	process fluid, tube-side fluid
utility	utility fluid, shell-side heat exchanging fluid
w, f	wall or fluid

order to reach high heat exchange performance. One alternative is to reduce the temperature difference between two fluids.

Besides energy efficiency, reaction quality is another aspect that may benefit from integrated design. Temperature control for exothermic or endothermic reactions has vital influence on the final process yield. However, many conventional equipment such as stirred tank reactors that incorporate heat transfer in the process, i.e. by using double jacket, external or internal coil, cannot supply or remove heat as efficiently as it is required by reaction. A compact device that combines reaction and heat transfer into a single equipment, i.e. using for instance a heat exchanger as a chemical reactor, the so-called *multifunctional heat exchanger*, could be an appropriate solution.

1.1. Micro/mini flow system

One of the methods to achieve compact, multifunctional exchangers is through the use of micro/mini scale channels (the so-called microfluidic equipment), as reviewed by Brandner et al. [7] and by Fan and Luo [8]. Advantages of microfluidic devices include high surface-to-volume ratio (named specific area, A/V, interfacial area in the case of mass transfer, and transfer surface area in the case of heat transfer), and improved safety. For example, a basic parameter to describe the "compactness" is the volumetric heat exchange capability, calculated as the product of overall heat exchange coefficient and specific area (UA/V). For micro channel heat exchangers this parameter is higher by several orders of magnitude than that of conventional devices. Moreover, safety and security in chemical and energy processes can be improved. Using microfluidic system, continuous process is easier to be realized with online monitoring. Reaction run-aways could be avoided by effective thermal management too.

However, to obtain a comparable productivity with that of conventional equipment, it is inevitable to put together a number of micro/mini-channels in parallel instead of mono-channel devices. This so-called *numbering-up* process is the key issue for industrial applications of microfluidic devices in large scale [9]. In that case, problem of fluid distribution from a single inlet port to an array of parallel micro-channels, and the reverse for collection, may have important influence on the global performance of multichannel equipment. Fluid maldistribution often deteriorates global performance of such devices. According to a study by Lalot et al. [10], a loss of heat exchange effectiveness could be up to 25% with the presence of maldistribution. Another particularity, in the case of chemical reaction, varied proportion of reactants caused by maldistribution may result in totally different products. As a result, distributing and collecting flow structures in a multichannel system need to be treated carefully.

1.2. Arborescent structure application

The arborescent structure, also known as tree-like structure, is a natural way of obtaining identical flow paths from "root" to "branches" or vice versa. The former case is the function of fluid distributor while the latter one is fluid collector. A general guideline on multi-scale design of fluid distributors can be found in Ref. [11], regarding both pressure drop and distribution character. Arborescent geometry is a "natural" option, which exhibits significant advantages in the numbering-up process in order to augment the productivity.

The fabrication difficulty usually prohibits the wide application of arborescent structures in industries because traditional fabrication methods are often constrained by size or complexity. However, the fast development of modern fabrication methods makes it more than possible but efficient to realize some non-conventional structures. While with 3D printing or other rapid prototyping methods like SLA (Stereo-lithography Apparatus) and DMLS (Direct Metal Laser Sintering), complex features could be rapidly realized without much intervention from technical personnel. The advancement of machinery technology also pushes the application of multi-scale, miniature arborescent structures.

The internal numbering-up of multiple channels using tree-like structures has been studied in our previous publications [12–17]. Firstly, the general philosophy of arborescent component and its scaling principles are introduced by Luo et al. [13]. Applications of similar structures in heat exchangers [12–14], mixer [15] and reactor [16,17] are successively reported. In most of these applications, arborescent structures are verified to be advantageous on global system performance compared with conventional fluid distributors and collectors.

As a continuation of the previous study on mixing performance by Guo et al. [17] over a multi-channel heat exchanger-reactor, this paper aims at giving a comprehensive investigation on its flow distribution and heat exchange performances. Firstly, the geometry of the heat exchanger-reactor is briefly described. Then, detailed experimental and simulation regarding flow uniformity, pressure

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