Experimental Thermal and Fluid Science 99 (2018) 407–419

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Residence time distribution on flow characterisation of multichannel systems: Modelling and experimentation

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

[a] ESIEE Paris, Université Paris Est, LIED UMR CNRS 8236, 2 boulevard Blaise Pascal – Cité Descartes, 93162 Noisy Le Grand, France
[b] Laboratoire de Thermique et Energie de Nantes (LTEN), UMR CNRS 6607, Université de Nantes, Rue Christian Pauc, BP 50609, 44306 Nantes Cedex 03, France

A R T I C L E I N F O

Keywords:
Residence Time Distribution (RTD)
Non-intrusive measurement
Flow distribution
Multichannel device

A B S T R A C T

Residence Time Distribution (RTD) is a frequently used tool in conventional process equipment and it provides internal flow characterisation by simple tracer tests. In this paper, we explore the feasibility of using RTD to identify fluid distribution uniformity in millimetric multichannel devices. Both theoretical modelling and experimental implementation are conducted to 16-channel systems. Theoretical modelling confirms the effectiveness of non-intrusive RTD measurements in evaluating flowrate distribution uniformity. Different influencing factors, such as channel corrosion, blockage, distributor structure, channel length or width variation, etc., can be reflected by RTD response curve. The experimental setup consists of a lab-developed RTD test platform coupling a fast camera and two miniflowcells capable to quantify rapid tracer concentration evolution through carbon ink visualization. The platform is particularly powerful for very narrow RTD measurement with residence time down to 1 s. With the platform, we investigate the RTD characteristics of a multichannel device under several flow conditions. Model correlation of the experimental data gives valuable information such as fluid distribution, plug-flow ratio and perfectly mixed volume.

1. Introduction

Significant progresses in Process Intensification [1,2] have been seen in last decades. They are characterised by compact size and enhanced performances in fluids mixing, heat transfer as well as chemical syntheses yields. However, industrial applications usually require large production rate which in general means high throughput, a weak point for most micro- or mini-devices. Numbering-up process [3–8] is then applied, in the form of 2D or 3D multichannel/layer systems or modular reconfigurable devices. Particularly for multichannel systems, the parallelisation of a large number of flow/mixing/reaction paths helps achieve industrial-level production.

Fluid distribution uniformity in multichannel devices is considered as a key issue to achieve high global performances. A number of studies in the literature have confirmed the influence of flowrate distribution in multichannel heat exchangers [9], mixers [10,11] and chemical reactors [12–14]. One of the existing difficulties in the evaluation of fluid distribution influence lies in the identification of flow distribution uniformity (in terms of flowrate). Non-intrusive measurements are necessary in case of non-transparent devices for which flow visualisation test is not applicable. This paper introduces our modelling and experimentation works on the development of a non-intrusive method based on Residence Time Distribution (RTD) characterization and its application to multichannel devices for their fluid flow distribution diagnostic.

1.1. Previous studies

Parallel millimetric channels can be configured to provide multiple functionalities including heat exchange, mixing and chemical reaction. Our previous studies [10,15,16] on a 16-channel device have demonstrated rapid mixing effect (with micromixing time down to 10 ms) and compact heat exchange property (with the overall heat transfer coefficient being in the range of 2000–5000 $W\,m^{-2}\,K^{-1}$). All these performances are thanks to a special tree-like structure that serves as fluid distributor and collector. By using such a nature-inspired manifold, the flow distribution non-uniformity is estimated to be lower than 10% under test flow conditions.

However, once channel flowrates differ among channels (non-uniform distribution, or maldistribution), the global performance is expected to degrade in most cases. Regarding micromixing and chemical reaction, uneven fluid distribution can result in unbalanced reagents composition thus totally different reaction kinetics. Shown in Fig. 1 is the link between fluid residence time and micromixing time, previously

* Corresponding author at: ESIEE Paris, Department SEN, 2 bd Blaise Pascal BP99, 93162, Noisy Le Grand Cedex, France.
E-mail address: xiaofeng.guo@esiee.fr (X. Guo).

https://doi.org/10.1016/j.expthermflusci.2018.08.016
Received 3 December 2017; Received in revised form 9 July 2018; Accepted 13 August 2018
Available online 15 August 2018
0894-1777/

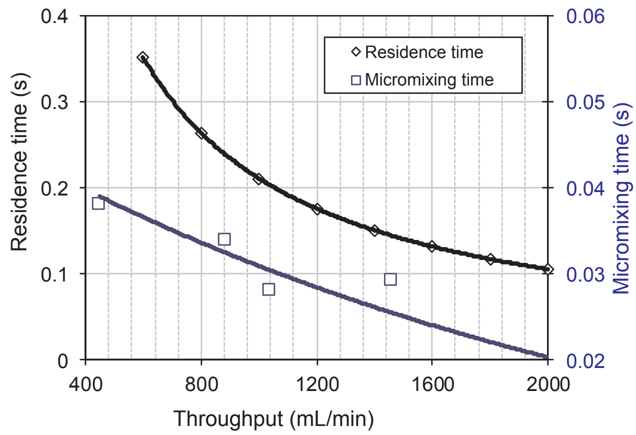

Fig. 1. The link between residence time and micromixing time in a static micromixer.

measured inside the 16-channel device [16]. It can be seen that, without a mechanical aided mixing, the two time variables are closely related and dependent on the channel flowrate. In other words, uneven flowrate distribution in a multichannel device may result in different micromixing time among channels, implying less controllable syntheses and heterogeneous final products.

In some specific cases, uneven fluid distribution may have positive influence on mixing. As in the study of Su et al. 2015 [17] on a multichannel zigzag microreactor, if the overall flowrate is kept the same, partial channel blockage may enhance mixing since more fluid perturbation happens in non-blocked channels with higher flowrates. In case of gross maldistribution, stronger fluid impingements in collectors also enhance the mixing process. However, the above conclusions only are applicable only under two conditions: (i) the mixing should be slow so that it does not finish before going into the collector zone, and (ii) a higher pressure loss with the same overall flowrate guaranteed by a pump. Our study focuses on straight pipes that will be used for rapid mixing/reaction applications and we suppose that they all require uniform fluid distribution for better performance.

As the influence of flow distribution uniformity on various performances of multichannel device is significant, the perfect reproduction of single pipe performances is strongly expected during numbering-up process. The ability to predict or identify the fluid distribution uniformity in a multichannel device by a non-intrusive experimental method is hence helpful.

1.2. Existing methods in fluid distribution identification

Main methodologies in the diagnostic of fluid distribution in multichannel devices can be categorized by numerical simulation and flow visualization. The use of non-intrusive tool such as RTD should be much helpful yet not sufficiently advanced in the literature.

CFD (Computational Fluid Dynamics) simulation is an interesting and practical tool intensively used for the prediction or characterization of hydrodynamic and/or thermal properties of multichannel devices, sometimes with the purpose of structural optimization. A number of studies using CFD tools have been reported in the literature [18–21]. Nevertheless, it should be noted that current CFD techniques still have some difficulties in correctly describing turbulent flows, vortex or curvature flows and multi-phase flows. Moreover, CFD results need to be validated by experimental measurements.

Besides numerical methods, existing experimental techniques for the evaluation of fluid distribution are limited to visualizations by color, pH indicator or fluorescence tracers [22–24]. Other intrusive experimental methods such as Hot Wire Probe (HWP), Doppler Ultrasonic Velocimetry (DUV) are compared by Boutin et al. [25]. But the above-listed techniques give only single point measurement other than detailed flow distribution information. Concentration measurement using salt as tracer [26] can be an effective solution for conventional devices. When comes to millimetric device that have short residence time, this method is limited by the sampling rate of conductometer. PIV (Particle Image Velocimetry) [25,27] and LIF (Laser Induced Fluorescence) [28] measurements provide quantitative velocity distribution inside certain flow configurations, but under specific conditions. First, the visualization is usually limited to simple or single-pipe devices but not adapted to 3D complex configurations. Second, PIV or LIF measurements require that the studied structure being transparent [28] in accordance with the wave length of the laser source.

The development of a non-intrusive tool for fluid distribution characterization based on inlet-outlet detection should be more practical for the identification of general multichannel flow systems. To the authors' knowledge, very few studies in the literature addressed the fluid distribution issue by RTD tool. Detailed RTD analyses merit being involved to explore the relationship between RTD characters and the flow distribution uniformity.

1.3. RTD and its application

Non-intrusive tracer test has been widely used in process engineering except for quantitative fluid distribution determination. After the pioneer work of MacMullin and Weber in 1935 [29] and several classical interpretations of RTD by Danckwerts in 1953 [30], extensive applications have been found in the field of chemical engineering. Macro-mixing and hydraulic characteristics of a process device could be reflected through examining the RTD curve [31]. RTD has also been used to predict the chemical reaction conversions by combining chemical kinetics and RTD analysis [32] or to determine optimal design parameters of tubular reactors [33]. Besides conventional RTD models for CSTRs (Continuous Stirred Tank Reactor) and PFRs (Plug Flow Reactor), some recent applications in multichannel systems in the aim of flow and mixing characterisation attracts some attention too [34–38]. In particular, recent works by Wibel et al. [39] investigated the impact of inlet/outlet volumes and uneven flow distribution on the RTD characters of micro devices consisting of an array of parallel microchannel, by both CFD simulation and experimental characterization.

For miniaturized process devices, one of the challenges to conduct a RTD analysis lies in the choice of tracer and its detection instrument. Especially for non-transparent devices, particle or dye visualisation [40] are generally impossible. Dong et al. [41] developed single channel Ultrasonic Microreactor and studied the effect of ultrasonic field on the mixing and RTD. The mechanism of ultrasonic induced cavitation (bubbles sizing 100–200 μm) intensifies radial mixing and reduces axial dispersion within the reactor channel (characteristic dimension from 250 μm to 1 mm). Their RTD measurements are based on UV–Vis spectrometer tracing 5 g/L uranine solution. This technique is more adapted to long residence time (around 100 s in their case). For very narrow RTD measurement, the spectrometer's sampling time may limit its application. In conclusion, quantitative fluid distribution (in terms of flowrate) determination by an easy-to-use RTD measurement is still lacking. Moreover, due to short residence time and narrow RTD curve of millimetric devices, traditional methods like conductivity measurement using salt as tracer [26], become limited by sampling rates. Developing a rapid RTD detection platform applicable to micro- or mini-fluidic devices is then of practical significance.

1.4. Current study

The main contribution of this study is to demonstrate the utility of RTD tool for the characterization of fluid distribution uniformity in multichannel devices. The study begins with the modelling of the RTD behavior of multichannel device with non-uniform distribution assumptions; then, an experimental platform applied to a previously