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Introductory Chapter: An Overview of Advances in Microfluidics and Nanofluids Technologies

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1. Introduction

Both microfluidic and nanofluids are rapidly growing and hugely potential technologies which emerged as multidisciplinary research fields. While microfluidic technology began with the development of the first lab-on-a chip in 1979 microfluidic research had its first step forward only when Manz introduced the idea of μ -TAS (Micro total analysis systems) in 1990 [1]. Other main timelines of the development of microfluidic technology include introduction of microfluidics in cell biology and biochemistry in 1994, employing PDMS (polydimethylsiloxane) in microchips production in 1998, introduction of digital microfluidics in 2000, investigations on microfluidics cell culture systems in 2004, development of organ-on-chip technology between 2005 and 2010, emergence of paper-based microfluidics in 2007, application of 3D printing in microfluidic technology in 2010 and the latest development of microfluidics for theranostics between 2012 and 2015 [2, 3]. Microfluidic technology deals with small amounts (i.e., microliter or nanoliter) of fluids (liquids and gases) in micron or sub-micron size devices/systems/geometries. Microfluidics is a very popular research field which can be evidenced from the rapid growth of numbers of publications on this topic (**Figure 1**). Year-wise publication data on microfluidics for the past two decades (data obtained by searching topic: “microfluidic” in Web of Sciences on 10th May 2021) are presented in **Figure 1**. The impact and importance of microfluidic technology can be manifested from its diverse real-world applications ranging from virus detection and bioanalytical, cell manipulation and separation, 3D printing, paper microfluidics to anticancer drug screening as highlighted in the following section. The advantages of microfluidics include very small quantity (e.g., microliter) of sample or reagent usage, contamination risk reduction, low cost (e.g., for analysis/diagnosis), automation, enhanced sensitivity, accuracy and reliability. Although different materials have been used, PDMS is currently the most widely used material for the fabrication of microfluidic devices and systems.

On the other hand, nanofluids, which is a new class of heat transfer fluids coined in early 1990's [4, 5] have also attracted tremendous attention from the researchers due to their enhanced thermophysical properties, potential benefits, and numerous applications [6–9]. **Figure 1** also shows publication records on nanofluids during the last two decades and the number of publications on nanofluids (search by the topic: Nanofluids) increases exponentially. It is to note that nanofluid is a much smaller

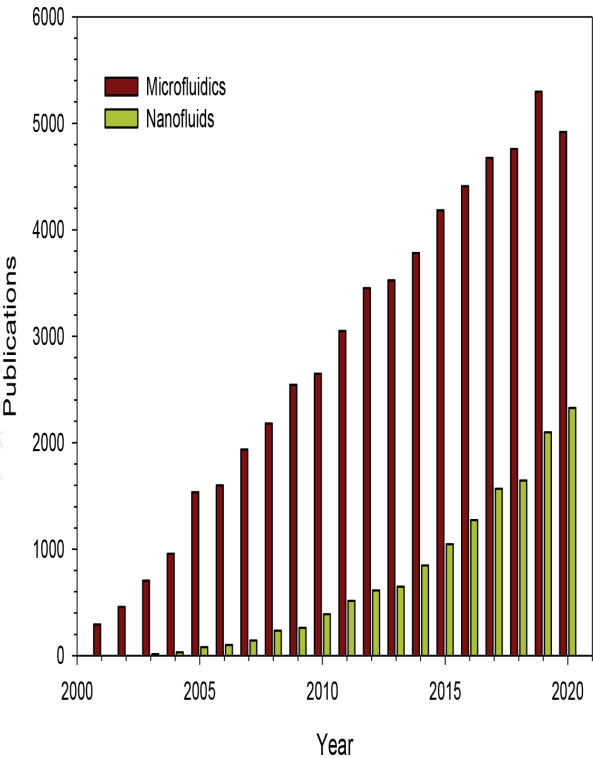


Figure 1.
Microfluidics and nanofluids related publications from 2001 to 2020 (source: Web of science).

field of research without any (noticeable) real-world applications compared to microfluidics. Nonetheless, these numbers indicate research activities and popularity of both research fields. Another important aspect of nanofluids is that having superior properties and nano-sized particles, they can be applied to microfluidic systems and devices which can result in improving performance and diversifying the applications of both nanofluids and microfluidic technologies [10, 11]. Nanofluids also span a wide range of potential applications starting from thermal management, energy conversion to nuclear reactor. However, this field is far from developing, exploring its benefits, and exploiting its real applications. The main challenges of nanofluids research are their inconsistent data, unidentified underlying mechanisms for the observed results and maintaining their long-term stability. The progress of the nanofluids research is briefly overviewed in the following section.

Since both microfluidics and nanofluids fields are well established and reported in the literature and textbooks [2, 3, 6–9, 12, 13], they will not be elaborated further. However, advances, applications and challenges of these technologies are highlighted in this chapter.

2. Advances in microfluidics

2.1 Global market status

Microfluidic technology is not only attractive to researchers and academics as an emerging research field but also to industrial people as its market is growing rapidly. According to a report by Yole development [14] currently there are 700+ microfluidic related companies worldwide yielding product revenues of around 7 B (billion) dollars in 2017. Also, there are 4500+ published patents only on microfluidic technology-based diagnostics. It was also forecasted microfluidic product

market value to reach about 25 B dollars in 2025 [14]. The major contribution to this revenue is expected to come from new areas like clinical and point-of care diagnostics through microfluidic chips. Other areas such as optical actuations and drug delivery are also growing and are anticipated to contribute considerably to this huge market.

Recent research and development at the cutting edge of microfluidics technology span from 3D printing to virus detection. It is noted that microfluidic technology received more attention during COVID-19 pandemic due their potential in detection and diagnosis of this novel SARS-CoV2 virus. Common classifications of microfluidic technology are presented in **Figure 2**. Although continuous flow based microfluidic systems particularly for reaction and mixing are widely used, during the past two decades significant progress has also been made in research and development in droplet-based microfluidics [15]. Each of these main and subclassifications of microfluidics technology is well-developed or in good progress towards revolutionizing their respective area.

2.2 Development in application

During the past three decades applications of microfluidic technology increased considerably in a broad spectrum of scientific areas from biomedical (known as biomicrofluidics), chemical to MEMS thermal management. The most notable applications include immunoassays (a bioanalytical technique) used in pharmaceutical and clinical laboratories for diagnostics, DNA assays (capturing separation and detection of DNA etc), cell-based assays (known cell culture). A schematic of presentation of various fields of applications of microfluidic technology is provided in **Figure 3**. It can be seen that microfluidics really span a diverse field of applications starting from Lab-on-chip (LOC) to the food and agriculture sectors.

As a pioneering effort by the author nanofluids were studied in microfluidic geometries particularly in droplet-based microfluidics in order to explore new applications of nanofluids [10, 11, 16]. Thus, experimental investigations on the droplet formation and size manipulation of nanofluids in the microfluidic T-junction and flow focusing geometries were conducted. Besides temperature-dependent droplet formation at both geometries, effects of other factors such as presence of

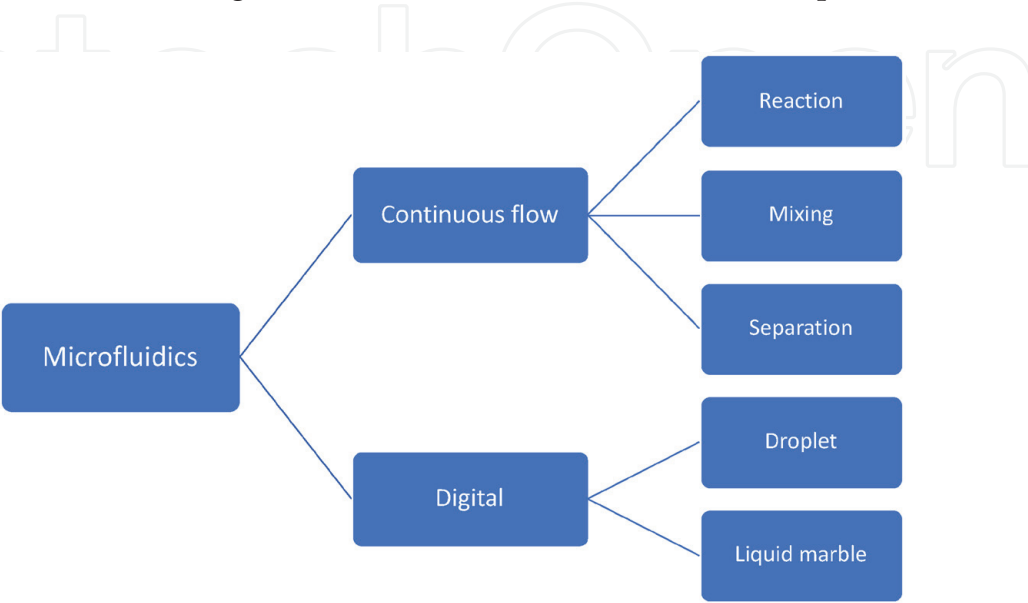


Figure 2.
Schematic of classification of microfluidic technology.



Figure 3.
Applications of microfluidic technology.

nanoparticles in aqueous fluid, depth of microchannel and flow rate on the droplet formation and size manipulation were investigated [10, 11, 16]. Although results are interesting and reveal the potential of nanofluids in microfluidics, more extensive research needs to be performed in this new combined field.

3. Overviewing nanofluids progress and challenges

The advancement in thermal management of modern equipment and systems are greatly impeded due to the limited cooling capabilities of conventional heat transfer fluids. Thus, there is an urgent need for heat transfer fluids with improved thermal properties and features. Nanofluids having found considerably higher heat transfer properties and features such as thermal conductivity, convective and boiling heat transfer compared to their base conventional fluids are believed to be capable of meeting such high cooling demands [8, 17–22]. With great features and properties nanofluids can be used for increased heat transfer and many other important fields of applications such as transportations (engine cooling or vehicle thermal management), microelectronics, solar energy technologies, micro-electromechanical systems (MEMS), electronics and instrumentations, heat exchangers, heating-ventilating and air-conditioning (HVAC), cooling electronics, microfluidics, defense, medical and so on (**Figure 4**). Researchers have also focused on studying nanofluids in diverse applications like- advanced cooling technologies, heat pipes, solar energy conversion and harvesting [8, 19, 23]. Being a multidisciplinary field and having numerous potential applications the impacts of nanofluids are very high. Although there are no recent market analysis or data for nanofluids, an estimation of the potential worldwide market for nanofluids was made sometimes ago and it was estimated to be over 2 B dollars per year only in heat transfer applications [21]. Majority of this market value came from cooling applications and

nanoparticles (main component of nanofluids). Although extensive research works have been performed particularly during the past decade, nanofluids real applications and benefits are not yet achieved. Thus, more systematic and careful research works on nanofluids are still necessary.

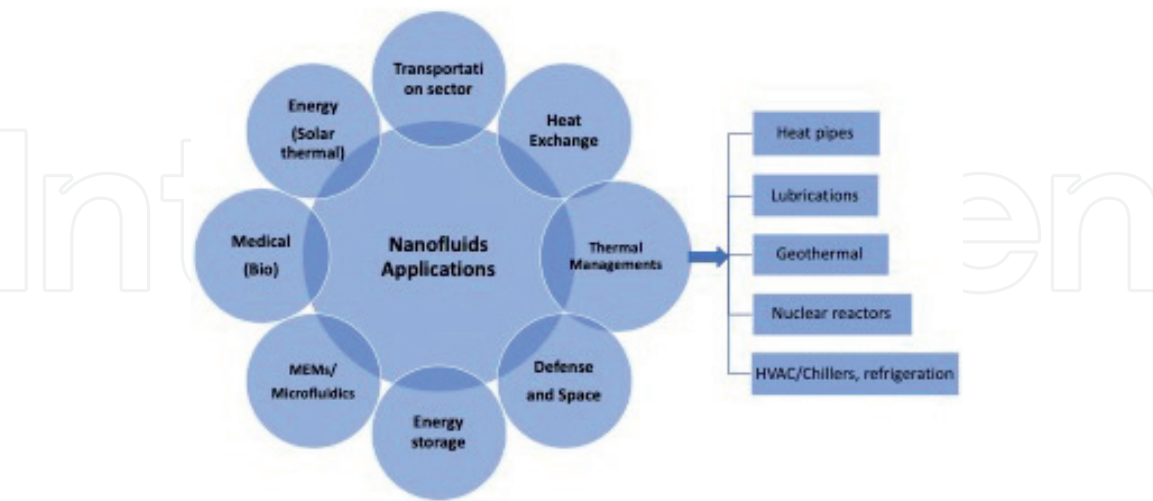


Figure 4.
Applications of nanofluids.

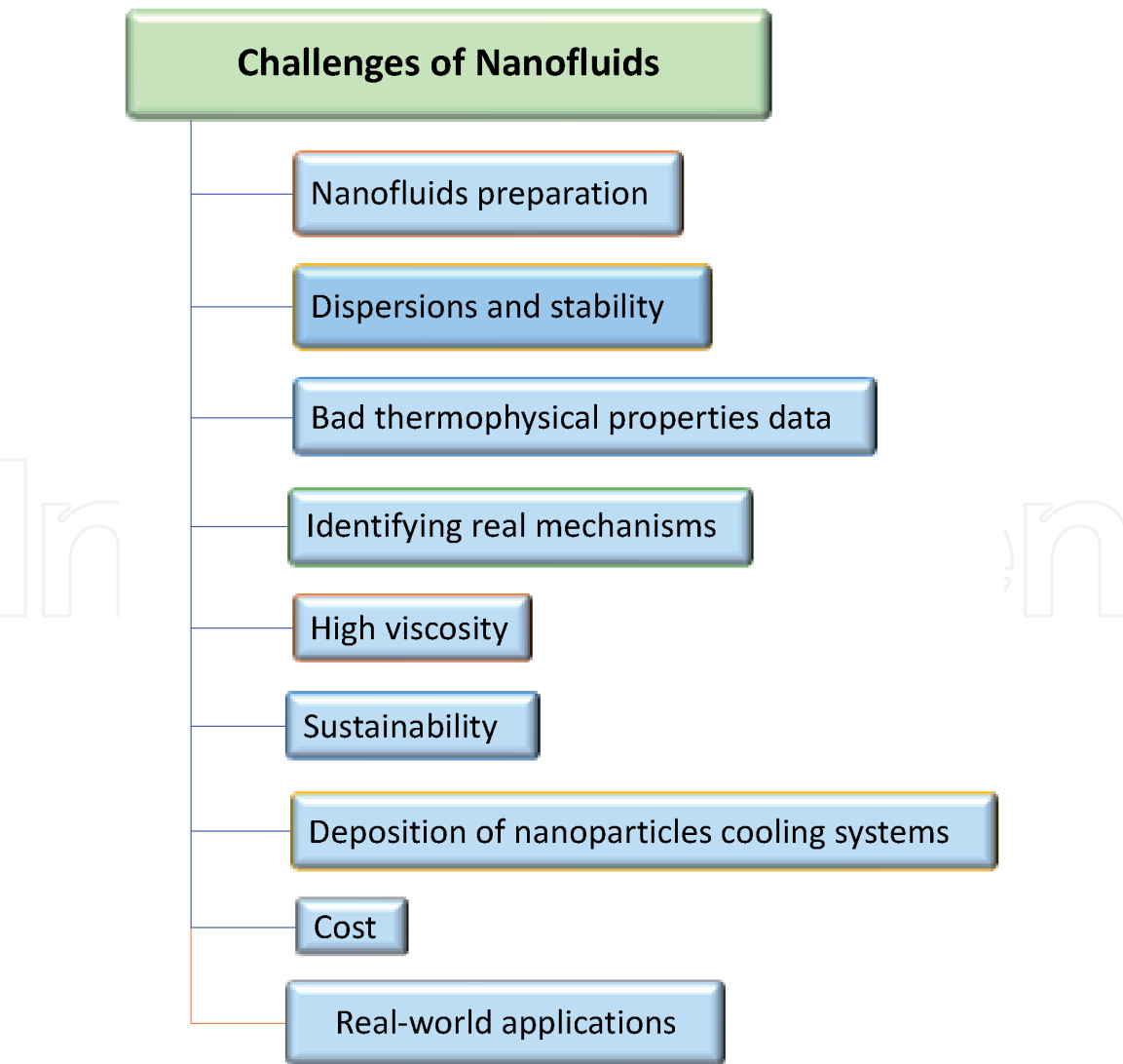


Figure 5.
Some key challenges of nanofluids.

Besides intensified research on various areas particularly on thermophysical properties and in several applications, research has been expanded to other new types of nanofluids like hybrid nanofluids and ionanocolloids (INC). Although research efforts on hybrid nanofluids have recently received increasing attention from researchers and findings from literature showed similar or better thermophysical properties compared to conventional nanofluids [24, 25], it is too early to explicitly identify their potential applications and benefits. On the other hand, ionanocolloids (suspensions of nanoparticles in ionic liquid) is another new type nanofluids which is in its early stage of research. However, ionanocolloids were found to exhibit superior thermal properties and show great potential compared to pure ionic liquids for many engineering applications including cooling [26–28].

Regarding research on thermophysical and heat transfer features, thermal conductivity is dominating the research producing more scattered data. However, the real mechanisms for the enhanced thermal conductivity of nanofluids are still inconclusive. Although many research efforts have been devoted until 2015 for the development of models for the prediction of thermal conductivity of nanofluids, the efforts have been declined recently despite no widely accepted models are available. This is due to the fact that no progress has been made on new mechanisms or physics-based understanding of underlying mechanisms. Nonetheless, despite above-mentioned impacts, potential applications, except few areas progressing on nanofluids towards developing them for real world applications are rather slow.

Nanofluids also possess serious challenges which impede their real progress towards application and human benefits. A list of main challenges of nanofluids research and development can be seen from **Figure 5**.

4. Remarks

This chapter gives an overview of progress, potential applications and main challenges of these two emerging and hugely important technologies. First it briefly discusses advancement of research and market values of microfluidics' followed by highlighting their main field of applications. Then, progress of and issues of nanofluids research and development is summarized besides bringing out potential application and challenges of this new class of popular fluids. This book is believed to be a useful reference source of information and knowledge in these two hugely important technologies.

Acknowledgements

This work was supported by the Fundação para a Ciência e a Tecnologia (FCT), Portugal through grant- PTDC/NAN-MAT/29989/2017.

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