# Principles and Applications of Droplet Formation in Porous-Wall Channels

Grundlagen und Anwendungen der Tropfenbildung in Kanälen mit poröser Wand

Von der Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

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Tag der mündlichen Prüfung: 21. Dezember 2016

Berichte aus der Verfahrenstechnik

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Shaker Verlag
Aachen 2017

**Bibliographic information published by the Deutsche Nationalbibliothek**
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: D 82 (Diss. RWTH Aachen University, 2016)



Printed in Germany.

ISBN 978-3-8440-5291-6
ISSN 0945-1021

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

To my parents.

# Acknowledgements

Behind each word, graph and picture in the present thesis is the help and support of many people that I'd like to thank in the following lines.

First of all, I'd like to thank Professor Matthias Wessling for supervising my thesis and giving me the opportunity of spending these wonderful years at the Chair of Chemical Process Engineering of the RWTH Aachen University. Beyond his scientific support, inspiration and motivation I will always esteem the trust he placed on me to investigate, create and assume such a variety of responsibilities that have enriched me.

I would also like to thank Professor Rob Lammertink in his role as external reviewer of my Ph.D. thesis and for his scientific input along the years in the 'winterschools'. My gratitude goes also to Professor Wolfgang Schulz for chairing my Ph.D. defense.

The Ph.D. time is indeed very worth living when you have such great colleagues as the ones I had during Ph.D. time. A very special thanks to those of the 'first generation' (and also those later adopted) for their friendship and support in the good and bad times. Here I'd like to particularly mention Sebastian and Serafin for being such great sparring partners and friends.

I also want to thank all the students who contributed in one way or another to this work with their drive, effort and ideas: Sabrina Dahmen, Tim Maßmann, Simon van Büren, Dennis Haasler, Anna Torka, Deniz Rall, Julia Thien, Kattayachalee Sattayakijkajon, Kristina Baitalow, Lara Kleines, Lukas Klein, Michael Alders, Christian Linnartz, Ivo Kühnrich, Hanna Wolff, André Welkner-Hoffmann, Sander Kraus, Sven Dörner, Christian Kneppeck, Marc

Decker, Michael Zier, Sebastian Holtwerth and Oskar Cheong. It was great working with you!

To all my friends for standing by my side in all these years, thank you very much. Here I want to particularly mention my Aachen family: Serafin, Simone, Hans and Alicia. Thank you for you unconditional friendship.

I want to thank my parents Rosa María and John and my brothers Dieter and Konrad for their love and support even if there was a big physical distance between us, your support was always present with me. I'm so lucky to have such a great family. Last but not least a huge thank you to my girlfriend Julia for her love, patience and encouragement throughout this time as Ph.D. student.

# Abstract

Droplets play a fundamental role in a large variety of fields such as pharmaceutics, food technology or chemical processing. These can be used as templates for production of polymeric spheres or capsules, as part of unit operation like liquid-liquid extraction or for cell encapsulation and drug delivery. Particularly when droplets act as templates, the control of size, shape and size distribution is paramount to ensure product quality. A new technology for droplet generation taking advantage of porous-wall channels addresses these requirements.

The method as presented in this thesis consists of a porous-wall channel, either as a hollow-fiber membrane or as an embedded channel in a porous flat-sheet membrane. Within these channels, two immiscible phases are brought in contact as coflowing streams and the liquid filament of the inner phase breaks up in the form of droplets either in a dripping or a jetting regime depending on the dominating forces. This is demonstrated both experimentally and with the help of CFD simulations that are able to depict the droplet formation mechanics occurring within the channels.

In addition to the study of the principle behind droplet break-up, a design for the generation of droplets at low micron ranges is presented. Furthermore, the potential of this technology is investigated for different applications of commercially available hollow-fiber membranes in the generation of aqueous two-phases systems (ATPS) droplets, droplet solidification, formation of elongated particles, and liquid-liquid extraction, being the latter the one showing most promising results.

# Zusammenfassung

Tröpfchen spielen eine wesentliche Rolle in vielen Bereichen wie in der Pharmazeutik, in der Lebensmitteltechnik oder in der chemischen Prozesstechnik. Die Tröpfchen können als Vorlage für die Herstellung von Polymerkugeln oder -kapseln, als Bestandteil von Grundoperationen wie in der Flüssig-Flüssig Extraktion oder für Zellverkapselung und Wirkstofffreisetzung verwendet werden. Insbesondere für das erste Beispiel ist die Kontrolle der Größe, Form und Größenverteilung von Bedeutung für die Produktqualität. Eine neue Technologie zur Tröpfchenbildung verwendet Kanäle mit poröser Wand um diese Anforderungen zu bewältigen.

Die hier präsentierte Methode basiert auf Kanälen mit poröser Wand, entweder als Hohlfasermembranen oder als eingebettete Kanäle in einer porösen Flachmembran. Innerhalb dieser Kanäle entsteht eine koaxiale Strömung durch den Kontakt von zwei ineinander nicht mischbaren Phasen. Die innere Phase zerfällt in Tröpfchen, entweder durch *Dripping* oder *Jetting* in Abhängikeit davon welche Kräfte dominieren. Dieses Verhalten wird experimentell und mit Hilfe von numerischen Strömungssimulationen dargestellt, die die Mechanismen der Tröpfchenbildung beschreiben.

Zusätzlich zu diesen Untersuchungen wird ebenfalls ein neues Design zur Herstellung von Tröpfchen im unteren Mikrometer-Bereich vorgestellt. Ferner werden die potentiellen Anwendungen von kommerziell erhältlichen Hohlfasenmembranen zur Bildung von Tröpfchen in wäßrigen Zweiphasensystemen, zur Herstellung von sphärischen und verlängerten Partikeln und für die Flüssig-Flüssig Extraktion untersucht. Dabei zeigt die letzte Anwendung die vielversprechendsten Ergebnisse.

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