Paving the future:
Introduction of 3D printing in Chemical engineering

[1]P. Stavárek, [1]M. Ujčić, [1]M. Večeř, [1]J. Havlica, [2]J. D. Araújo, [2]M. Alves, [3]C. A. Grande

[1]Institute of Chemical Process Fundamentals of the Czech Academy of Sciences v. v. i., Rozvojová 2/135, 165 02 Prague, Czech Republic, e-mail: stavarek@icpf.cas.cz
[2]CEFT, Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto. Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[3]SINTEF Industry. P.O. Box 124. Blindern, N0314, Oslo, Norway

PRINTCR3DIT
Process Intensification through Adaptable Catalytic Reactors produced by 3D Printing
Project ID: 680414

Deliverable 5.6
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Table of Contents

1. Description of the Deliverable

This deliverable addresses opportunities and challenges that are related to the introduction of 3D printing technologies in education, with special focus on chemical engineering and related fields. To assess the status, a short survey about 3D printing implementation in education has been conducted and discussion of acquired responses is provided and discussed. Additionally, a description of content (syllabus) for a basic course of 3D printing has been prepared as well as a short list of training examples.

1.1. Purpose

This deliverable aims to promote and support the utilization of 3D printing technologies within chemical engineering educational programmes at universities. The materials provided and disclosed in this deliverable can be treated as supporting and inspirational tools for establishing new subjects at universities. Such courses can introduce students to the different 3D printing technologies and how their utilization can be exploited to solve chemical-engineering problems.

1.2. Contents

The deliverable contains the questionnaire about 3D printing status in education at a European level. In total there were 34 responses acquired from 21 European universities that are discussed here. The next part of the document contains syllabus (course materials) for introduction the 3D printing topic and three examples for practical laboratory trainings with focus on 3D printing utilization in field of chemical engineering.

2. Introduction

From the early 1980's when the first 3D printing equipment and materials were developed, 3D printing has grown and expanded to numerous fields of application. Nowadays, the umbrella of 3D printing covers several different technologies that allow to manufacture parts with materials such as metals, ceramics, polymers, photo-polymers or biomaterials. The field is also known as "additive manufacturing" since the technologies are used to produce parts through addition of layers of material rather than its removal. This computer-controlled process allows fabrication of a desired prototype from a CAD model in a relatively short time. The precision depends on the material and technology used; in general, it is lower than the current computer numerical control (CNC) technology for example, but on the other hand, it can overcome some of its geometrical limitations. Moreover, instead of being a "negative" technique for manufacturing, the creation of objects by successive construction of layers, result in net savings of materials, something which is particularly true for complex geometries. Therefore, the largest field of utilization of 3D printing technologies is for fast development of physical parts or assemblies known as Rapid Prototyping. Main markets for such parts are the automotive [1] and aerospace industry [2]. Today, utilization of 3D printing is far beyond that. 3D printing can be found in medical science for bone implants or

[1] M. Cotteleer, J. Holdowsky, M. Mahto, J., Coykendall, 3D opportunity for aerospace and defense, Deloitte report, available online since June 02, 2014: url

[2] C. A. Giffi, B. Gangula, P. Illinda, 3D opportunity for the automotive industry, Deloitte report, available online since May 19, 2014: url

artificial tissue supports printing, in dental medicine, pharmacy, jewelry, architecture and many more.

Dynamic development and wide commercialization of 3D printing in last decade was initiated (among others) by Fused-Deposition-Modeling (FDM) patents expiration in 2009. The consequent development of the field brought the affordable 3D printing devices, which made the technology available to a broader community both on professional and amateur level.

Despite the good readiness of 3D printing technologies, the potential of 3D printing is not yet completely exploited. Chemical engineering is one of fields where the 3D printing has not penetrated yet, even though it presents high potential for customized reactor design, optimization and process intensification. One of the main reasons for such a situation is a lack of well-educated professionals in 3D printing technologies. Therefore, PRINTCR3DIT project addresses the problem and focuses on wider implementation of 3D printing technologies in chemical-engineering programs. During the project, the course materials of 3D printing basics were prepared containing practical examples of 3D printing utilization for chemical-engineering problems. We have used this material with university students that attended the pilot course as an optional subject. Their interest as well as the responses from the questionnaire triggered the organization of the first additive manufacturing summer school that will take place in August 2018 in Prague.

3. Current state of the 3D printing education at universities

With the pursue of monitoring the current situation of 3D printing as a topic and its presence in chemical engineering education, a questionnaire was prepared and distributed among different EU universities. Our evaluation of the results is also included in this Deliverable.

3.1. Questionnaire about 3D printing education in chemical engineering

The questionnaire contained 10 questions focused on aspects such as whether the students have some 3D printing background, or if there are any subjects already available that include 3D printing topics in any stage. If so, respondents were asked to provide subject name, field of focus and to what kind of 3D printing technology and 3D modelling software students have access to. In addition, we aimed at collecting the respondent opinions about current barriers in wider implementation of 3D printing in education.

The questionnaire used an on-line platform (Google Forms, see here) and was distributed among more than 60 contacts at technical universities involved in chemical engineering education around Europe, and through social media. The 34 replies from 21 different universities were collected in total. The purpose of this survey was to provide a first overview about the 3D printing implementation at EU universities; however, the aim was not to perform an extensive survey over all EU universities that would require much more resources. The replies represent opinions of university professors and university employees and cannot be considered as official statements of the university authorities.

3.2. Questionnaire results

University	Country
Université de Bordeaux	France
University of La Rochelle	France
Aquitaine Science Transfert	France
Université de Limoges	France
Université Nantes	France
Lorraine University	France
University of Jan Evangelista Purkyne in Usti nad Labem	Czech Republic
České vysoké učení technické v Praze	Czech Republic
VSB-TU Ostrava	Czech Republic
Brno University of Technology	Czech Republic
University of Chemistry and Technology in Prague	Czech Republic
University of Zagreb	Croatia
TU Eindhoven	Nederland
Delft University of Technology	Nederland
University of Porto	Portugal
Complutense University of Madrid	Spain
University of Edinburgh	United Kingdom
TU Dortmund	Germany
KU Leuven	Belgium
University of Belgrade	Serbia
Babes-Bolyai University	Romania
Total	21

Country	Number of responses
France	14
Czech Republic	8
Portugal	1
Croatia	3
Spain	1
United Kingdom	1
Serbia	1
Nederland	2
Germany	1
Romania	1
Belgium	1
TOTAL	34

Figure 1 Answer to question 1: For me, the topic of 3D printing is

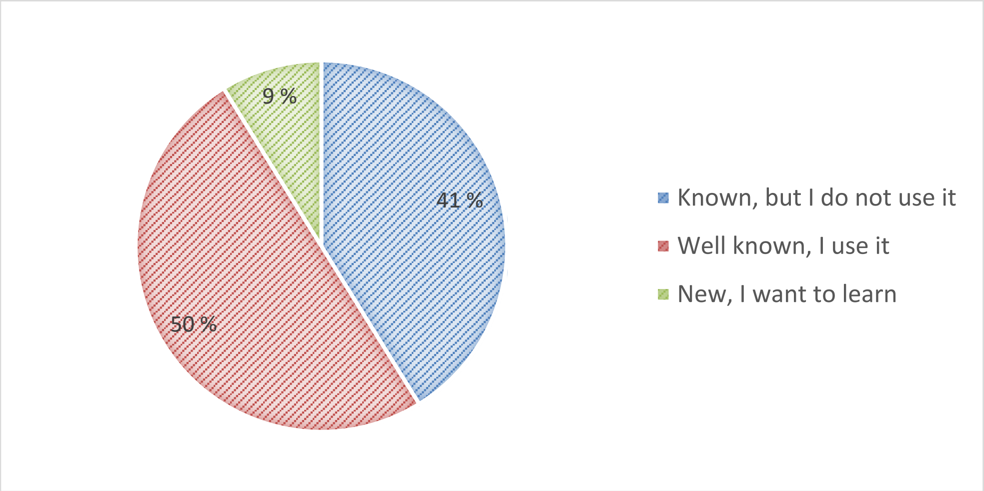


Figure 2 Answers to question 2: Do your students have a basic information about 3D printing?

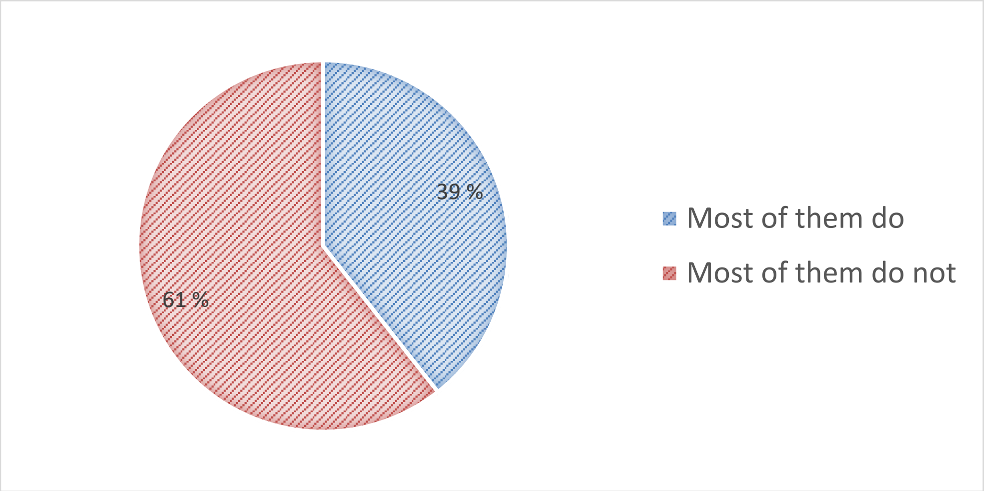


Figure 3 Answer to question 3: Is 3D printing seen as an interesting field of study/subject by your students?

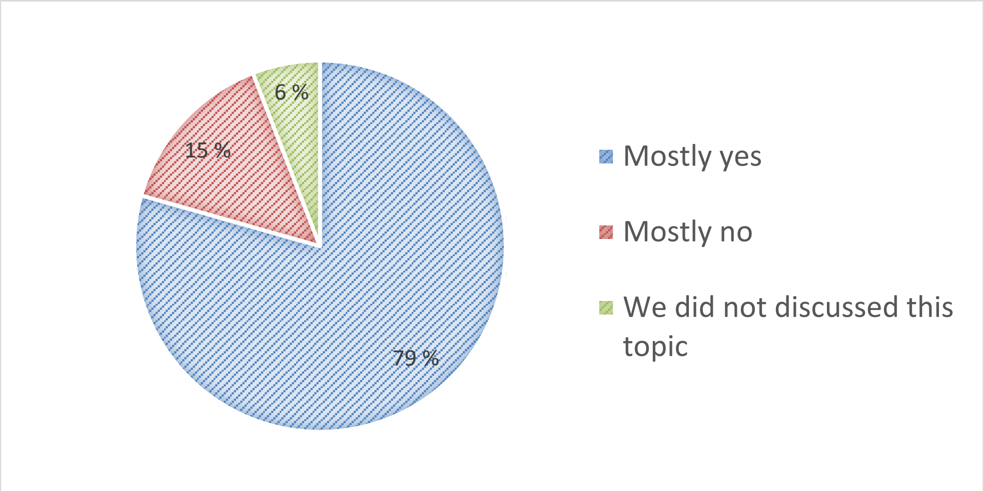


Figure 4 Answer to question 4: a) Is 3D printing a part of any current subjects?

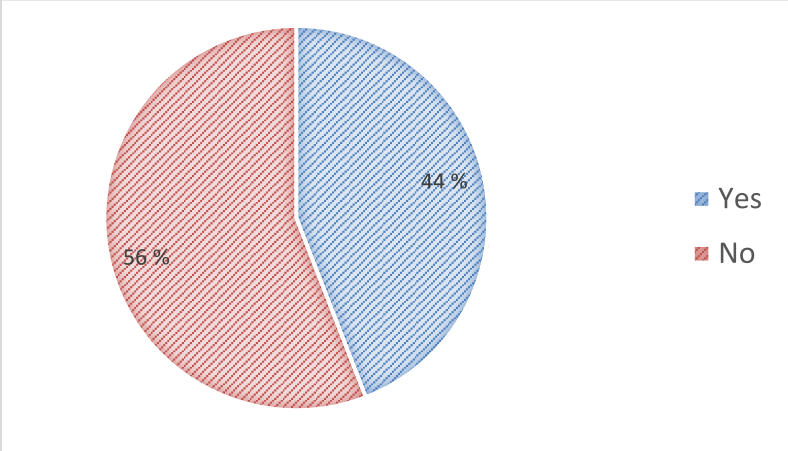


Figure 4 b) If yes, please specify the subject and field.

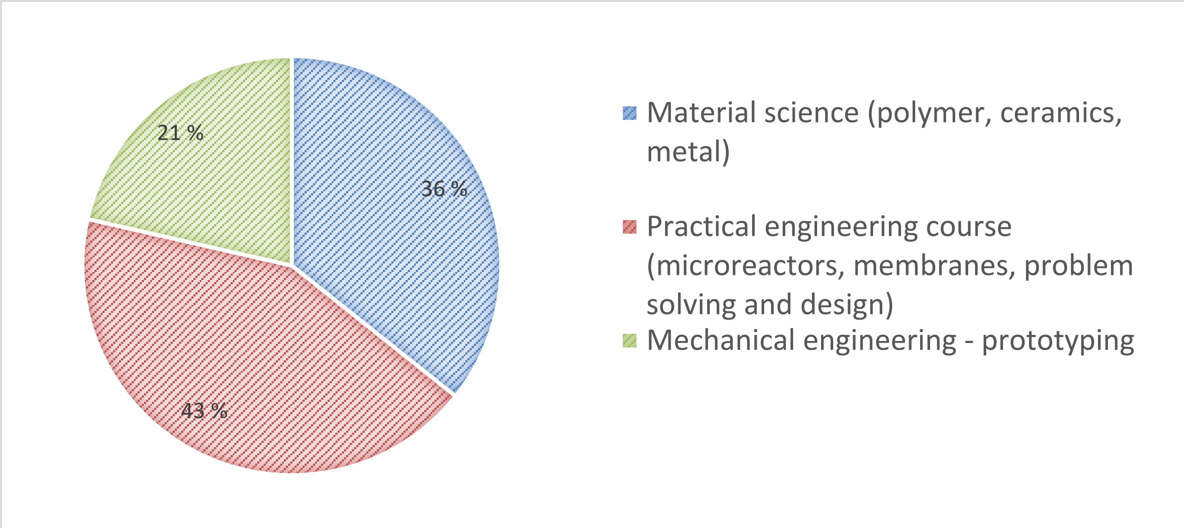


Figure 5 Answer to question 5: If answer to question 4 was positive, what technologies of 3D printing are students acquainted with?

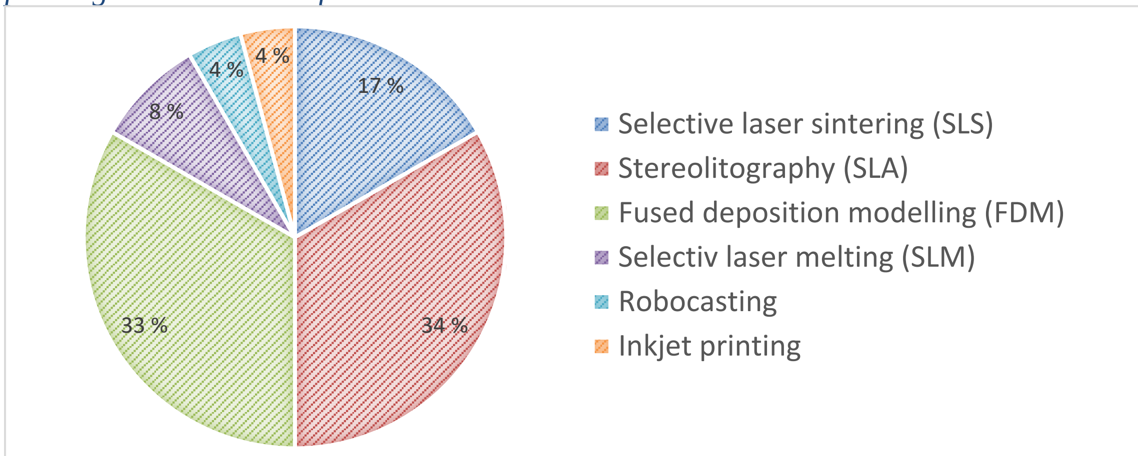


Figure 6 Answer to question 6: What skills required for using 3D printing do students learn within other subjects?

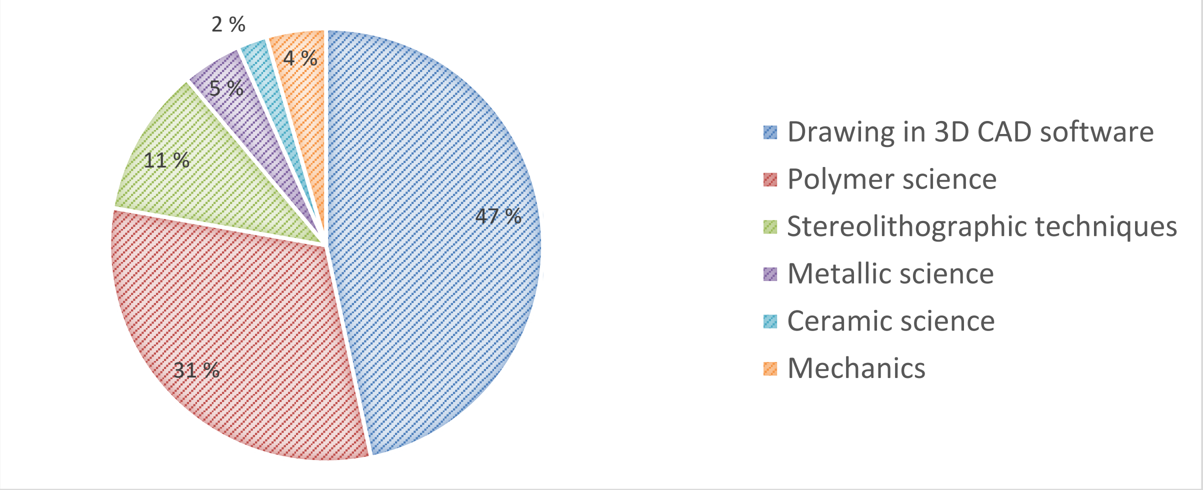


Figure 7 a) Answer to question 7: Do you think there are any obstacles to exploit 3D printing in chemical engineering and similar fields?

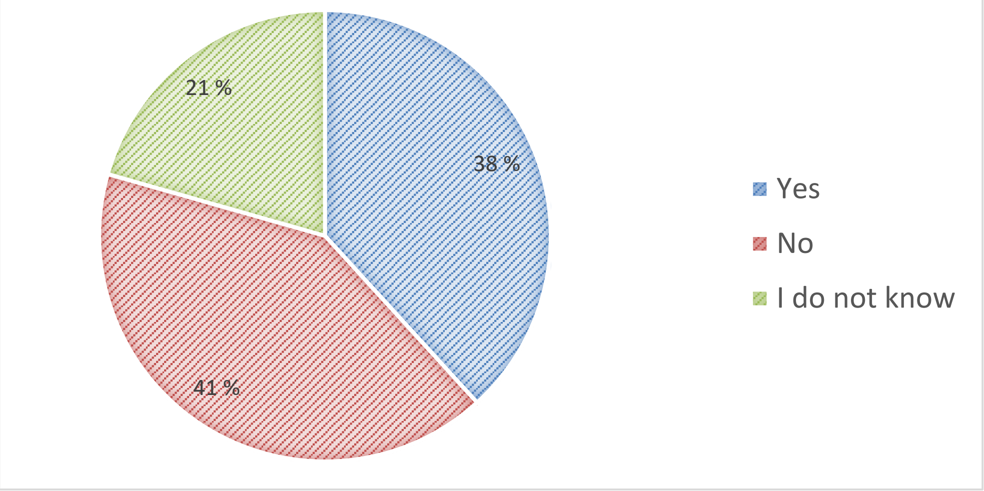


Figure 7 b) If yes please, specify.

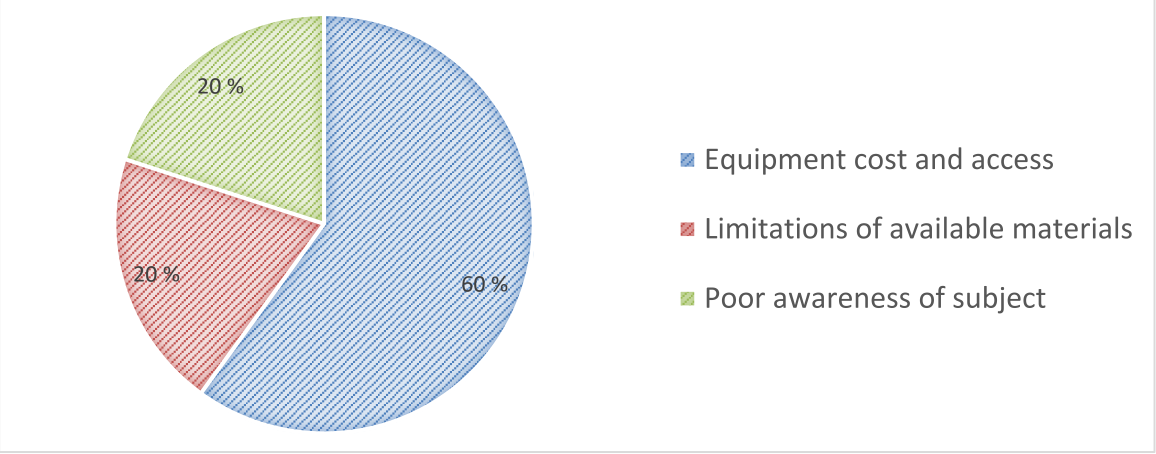


Figure 8 a) Answer to question 8: Would you welcome a subject focused on 3D printing or supplemental topic as a part of education at your school/university?

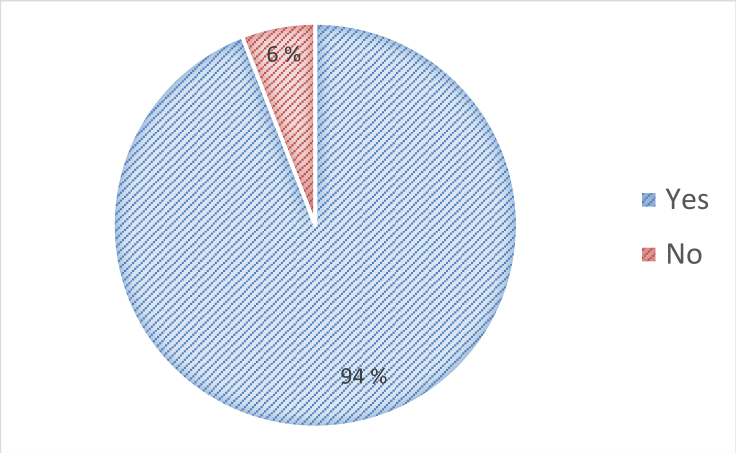


Figure 8 b): If yes, please write in which field.

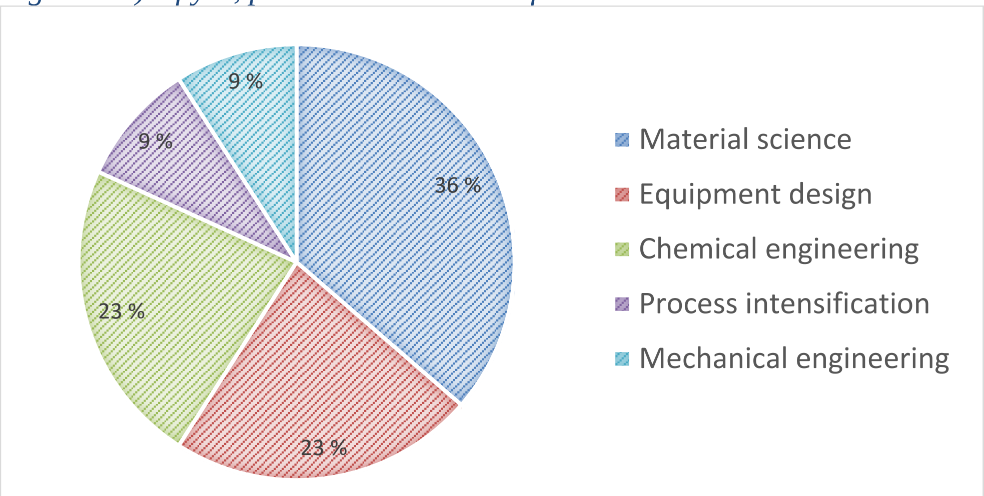


Figure 9 Answer to question 9: a) Would you consider purchasing a 3D printer in case of availability of the practical courses and tutorial texts?

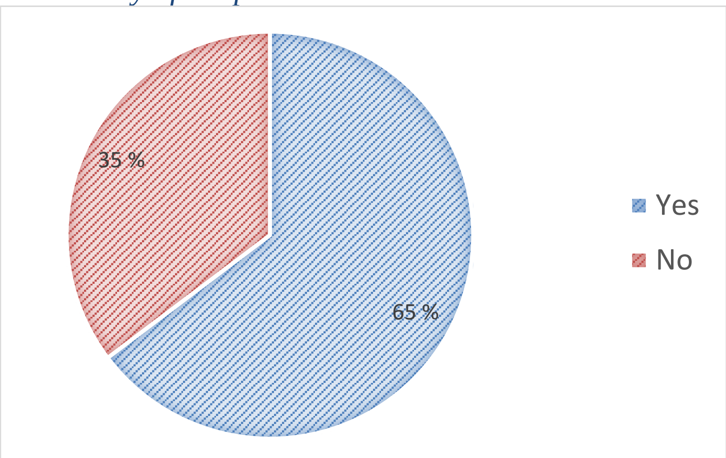


Figure 9 b) If no, please explain why.

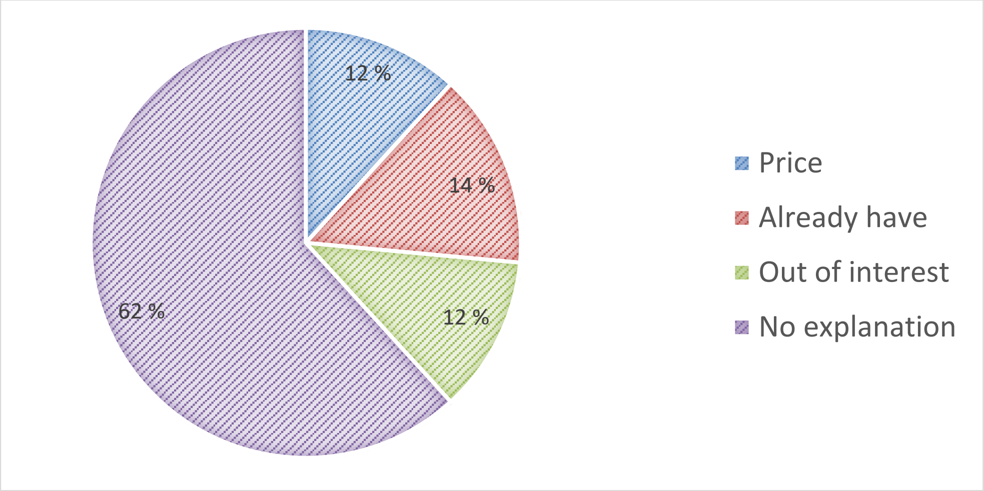
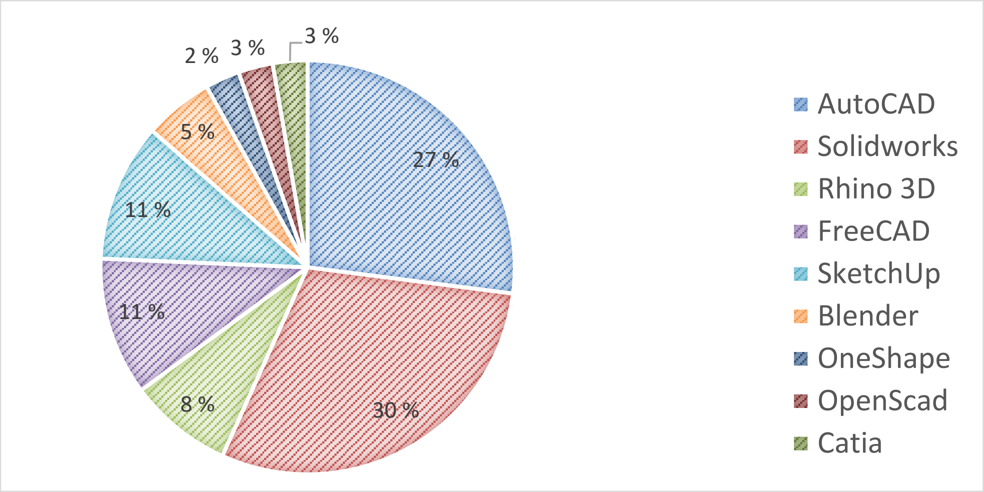


Figure 10 Answer to question 10: Do your students use any of the following software for 3D printing in other subjects?



3.3. Questionnaire results discussion

The additive manufacturing technology (3D printing) became a common part of our lives over the last years. Therefore, it is not so surprising that most people in academia has some knowledge about it and use 3D printing for their work (Figure 1). However, about 61% of them think that most of students do not have sufficient basic information about 3D printing (Figure 2). Despite of general knowledge of 3D printing technologies by professors and teachers (from the highly interested community), only 44% replied that students encounter the something related to additive manufacturing during their studies (Figure 4). This fact is in contrast with the reply, that for the most of students (79 %) the 3D printing is an interesting topic (see Figure 3) that might bring a valuable experience for their future professional carrier. This reflects a need for educational material, since there is a demand and a lack of lectures.

In the case that the 3D printing is part of education, it is a part of practical engineering courses (43%), material science courses (36%) or mechanical engineering courses (21%), see Figure 4 b).

For the universities that have access to the 3D printing technologies, the most exploited ones are the stereolithography SLA (34%) and fused deposition modelling FDM (33 %), followed by selective laser sintering SLS and melting SLM (17% and 8%). Robocasting and inkjet printing are the least common (see Figure 5). The SLA and FDM technologies are the preferred ones most probably due to their flexibility and relative low investment and operational costs.
The questionnaire also focused on finding common topics related to the 3D printing that are already a part of other subjects. The biggest intersections were found in teaching of 3D CAD software (47%) and material science, polymers 31%, metals 5%, ceramics 2% (Figure 6).

The respondents were also asked for their opinion about the existence of any obstacles that prevent wider exploitation of 3D printing in chemical engineering (see Figure 7). About 41% do not see any, 21% do not know, and about 38 % think that obstacles exist. As the most critical one, they pointed out the equipment cost and limited access to it (60%), limits in available materials for 3D printing (20%) and poor awareness of the subject (20%), see Figure 7 .
Further analysis of a survey data has shown that only about 14% of respondents have a 3D printer available at their workplace, see Figure 9 . Nevertheless, the important fact is that most of the respondents (94% as shown in Figure 8) would welcome new subjects focused on 3D printing to be implemented into the educational programmes focusing on material science, equipment design, chemical engineering, process intensification and mechanical engineering (Figure 8 b)). Furthermore, about 65% consider purchasing a 3D printer in case of availability of the practical courses and tutorial texts (Figure 9). For the rest, the most critical obstacle they find is the price of the equipment (Figure 9). Indeed, only one or two relatively affordable printers might not solve the issue on the university level but might be sufficient to initiate a program.

Last question was about what kind of 3D drawing software is available at the universities in order to have an idea about the focus in preparing materials for courses (Figure 10).

4. Experiences of education of university students from PRINTCR3DIT

4.1. ICPF, Prague

The ICPF in cooperation with University of Jan Evangelista Purkyne (Usti nad Labem) and VSB-TU (Ostrava) has prepared the materials for the course of Introduction of 3D printing into the chemical engineering. Materials consist of slides for lecture focusing on the 3D printing technologies in general, slides for lecture introducing the 3D modelling (CAD), and practical examples for demonstration of utilization of 3D printing for fabrication of a reactor and testing it in real operation or with a model chemical reaction. The materials are public and are available at: www.printcr3dit.eu.

The course of introduction into 3D printing for chemical engineering has been conducted in years 2016 – 2018 as a full day event (3 hours lecture, 3 hours lab work + evaluation). Within this period more than 50 students in small groups (3-6 students) attended the course and another 20 are registered for upcoming course in the summer semester of 2018. On basis of this course, gained experience and student's feedback, ICPF organizes with consortium partners the Summer school of additive manufacturing that will take at ICPF, Prague in August 2018. ICPF is in negotiations with University of Jan Evangelista Purkyne (Usti nad Labem, CZ) that expressed its interest in continuation of the 3D printing course in form of a regular subject in next academic year 2018-2019. This course will contain topics as described in section 5 below.

Figure 11 Students attending the Introduction into 3D printing course at ICPF

4.2. University of Porto

The PRINTCR3DIT team at the University of Porto promoted the direct contact of Chemical Engineering students (from the Faculty of Engineering of University of Porto - FEUP) with 3D printing technology.

In the first semester of academic year 2017/18, 67 students of the laboratory class Chemical Engineering Practice I (a discipline of the 3rd year of the Chemical Engineering Integrated Master - MIEQ) participated in the manufacturing steps of a fixed bed column distributor (Figure 16) using a 3D printer based on the Fused Deposition Modelling (FDM) technique. The intention was to make them aware of the practical impact and versatility that a 3D printer may offer to common chemical engineering setups, not only to create/materialize different designs, but also to renew/replace/improve parts of existing installations.

During the second semester of 2017/18, the presentation of two tools extensively used in PRINTCR3DIT (3D printing and CFD) was integrated in the lab classes of PEQ IV - Chemical Engineering Practice IV (a discipline of the 4th year of the Chemical Engineering Integrated Master) with an overall attendance of 64 students divided into 4 classes of 3 hours each (Figure 17). The main topics addressed were:

1. Introduction to additive manufacturing – techniques and main advantages of 3D printing;
2. Innovative potential of additive manufacturing in Chemical Engineering;
3. Printing of simple and more complex 3D geometries using a Stereolithography 3D printer;
4. CFD simulation results of a tracer experiment in one of the printed geometries.

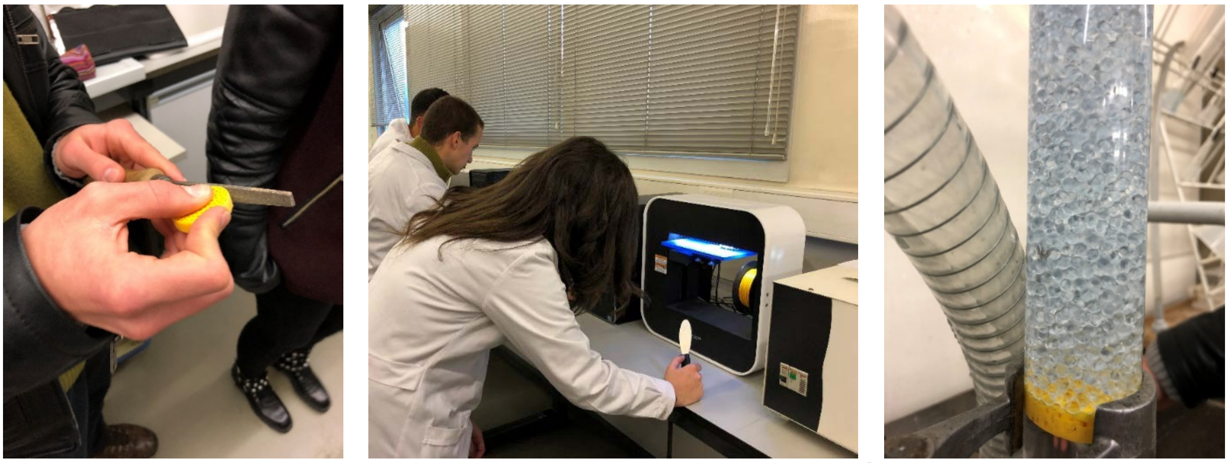


Figure 12 3D printing of a fixed bed column distributor with 3rd year students of Chemical Engineering at FEUP (Porto).

Figure 13 Presentation of additive manufacturing to 4th year Chemical Engineering students and printing of 3D geometries using the stereolithography technique.

Furthermore, a protocol was prepared to guide the students to perform the numerical simulation aforementioned in point 4 and get acquainted with the capabilities of CFD tools. This protocol includes the full description of the steps involved in a CFD simulation made in the commercial package ANSYS Fluent (more user-friendly for beginners): definition of the computational domain and boundary conditions (the mesh files were provided to the students to facilitate the work); definition of models to describe the system; solution methods; monitoring the convergence criteria; post-processing of data and extraction of main results. Two groups of students performed this work during the PEQ IV classes and the remaining students will be able to do it as an optional home exercise.

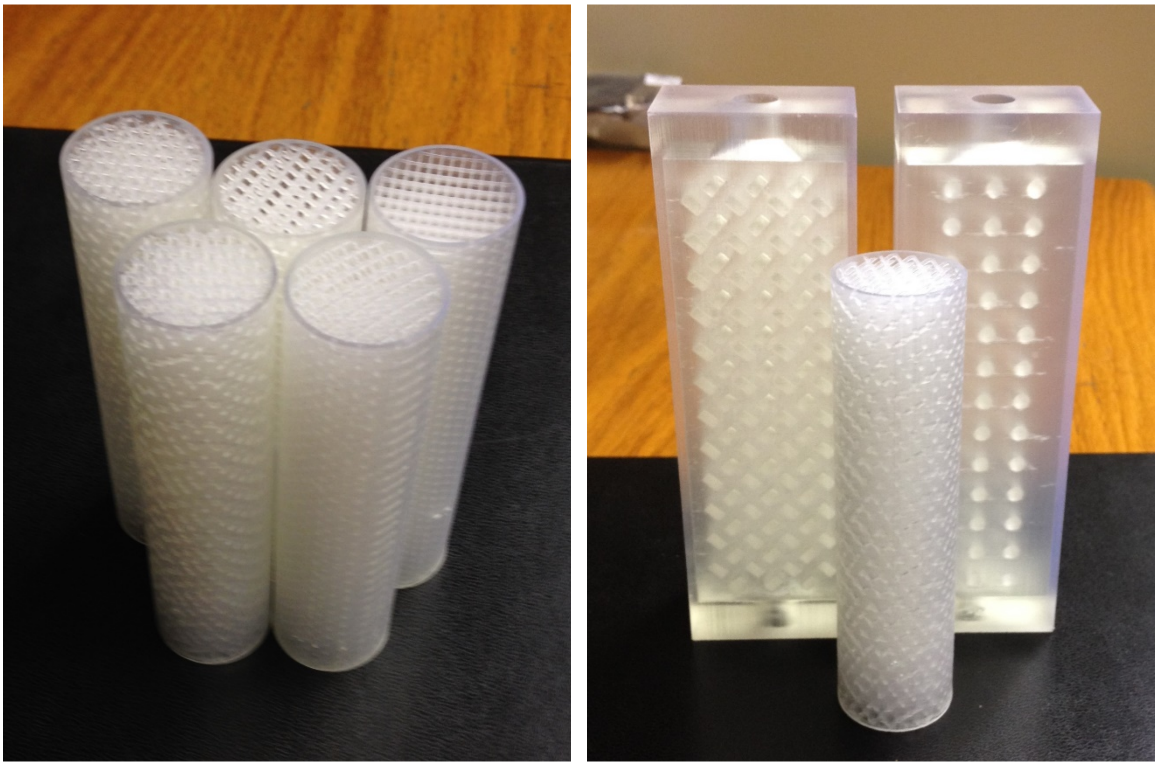


Figure 14 3D geometries manufactured with the SLA printer during the presentation to the 4th year Chemical Engineering students.

This first class of introduction to 3D printing methodologies in Chemical Engineering has received positive feedback and interest from students and teachers of the lab classes. Therefore, this class will continue and FEUP will implement it as a specific section into next year PEQ IV official programme. Our team is already in close collaboration with technicians of the Department of Chemical Engineering to prepare this section that will include a hands-on full approach in lab scale, i.e., the students will print specified 3D geometries prepared to be fitted into existing experimental setups; perform experimental tracer and homogeneous reaction tests; CFD simulations of the referred experiments; assessment and discussion of results.

The referred preparation includes defining a set of different geometries to study (and printing them), assembling the full setup for the experimental part, performing some experimental tests (to assess the setup) and the corresponding CFD simulations (to check the numerical procedure). These kind of activities will occupy one technician during 1 week but this effort will be necessary only in the first year. Regarding the execution of the planned full approach (3D printing + experiments + simulations), each student will have to dedicate around 6 hours with the supervision of one teacher. The dedication time of the teacher will be the same as in previous years for the PEQ IV discipline (3 hours per class). In terms of materials, since the students will work in groups of 2-3 elements, it is expected to be spend around 1 litter of Clear Resin for the Form 2 3D printer (cost of approximately 165€).

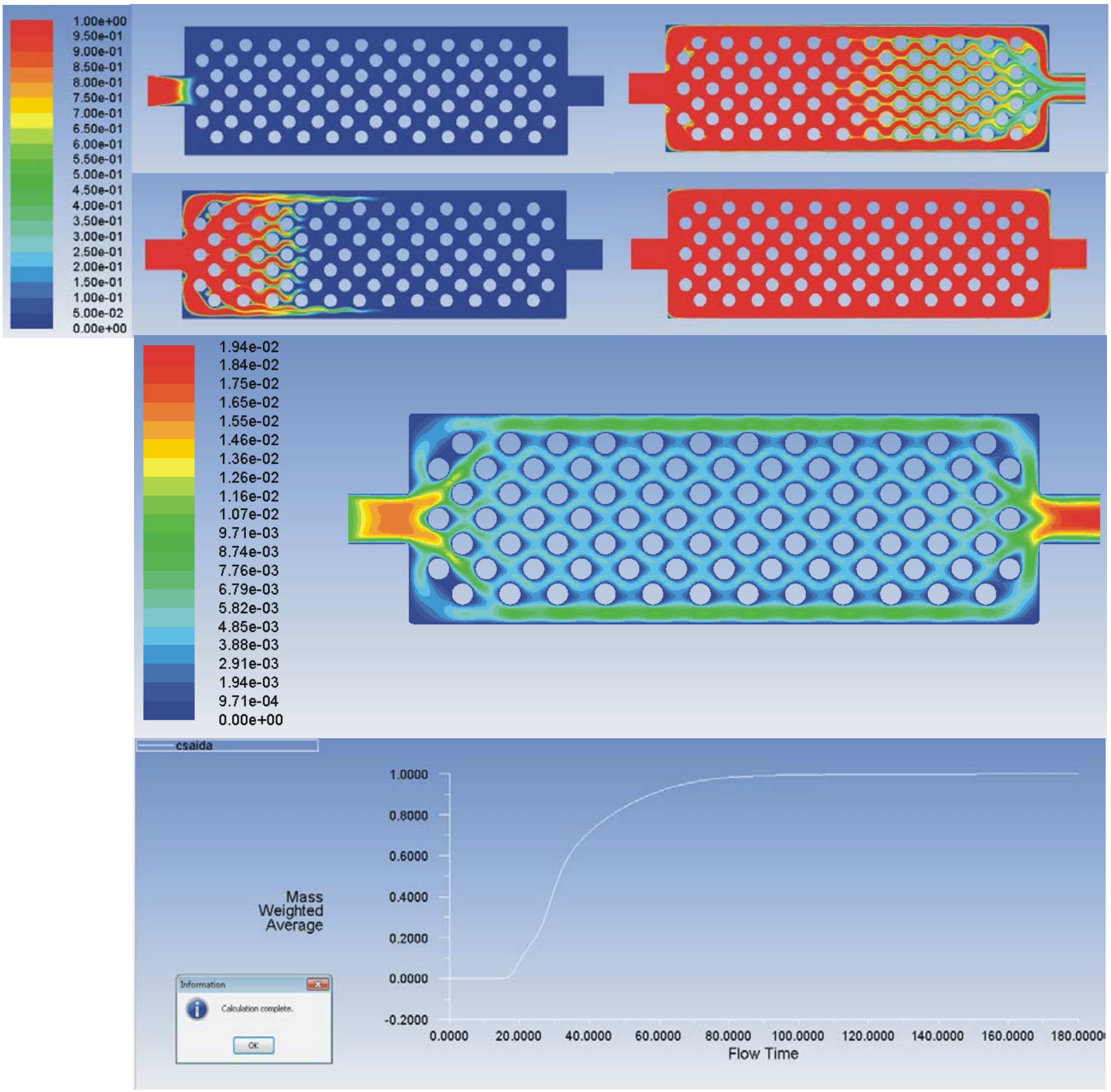


Figure 15 Illustrative results obtained by the students during the CFD exercise: tracer mass fraction fields for a sequence of times (top images); fully developed velocity field (middle image); average tracer concentration at the outlet boundary as a function of time (bottom image). The latter results allow the students to further analyse the reactor hydrodynamics in terms of residence time distribution, average residence time and presence of shortcuts and/or dead volumes.

4.3. Students internship (Erasmus programme)

Within PRINTCR3DIT, we have experienced technology and knowledge transfer between groups with existing expertise (Prodintec, Canoe and Sintef) to other groups that can support longer-term initiatives in education of chemical engineers (ICPF and FEUP).

We have also promoted another model for direct knowledge transfer using the Erasmus programme: students from master-programmes can make internships in partners having 3D printing infrastructure or access to develop their thesis work. One student from University of Porto (Núria Rebelo) developed her Master thesis work at SINTEF (in the period between February and June 2017 – thesis title: “Use of additive manufacturing in Chemical Engineering”) and another student (Joana Costa) from University of Porto is currently working at SINTEF (period March – July 2018) focusing on 3D printed catalytic supports (the work will also be used for her Master degree dissertation).

Other two students (Ivana Cevid and Filip Car) from Zagreb University, Croatia have been working at ICPF, Prague in the period March – July 2018. Ivana’s topic includes the development of a static mixer for a given neutralization reaction. The reaction was chosen with regard to allow for spectrometric measurement of conversion by a color indicator. Filip has been working on the characterization of different 3D printed structures from the two-phase pressure drop point of view.

This tool of knowledge exchange can also be seen as a longer-term effect contribution of PRINTCR3DIT project to train the next generation of chemical engineers for new methods.

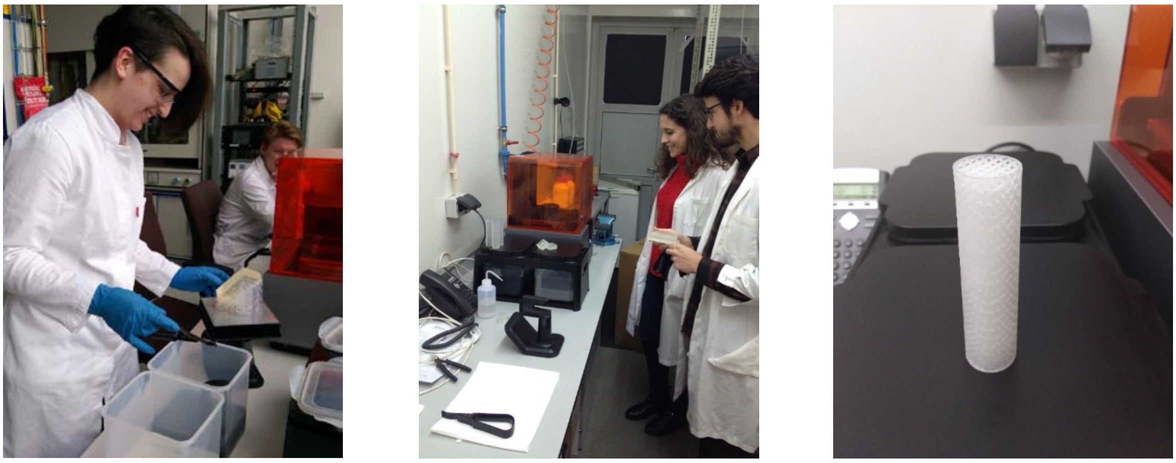


Figure 16MSc students during the Erasmus internship at SINTEF and IPCF

4.4. Summer school 2018: First European school for additive manufacturing applied to chemical industries

The goal of this summer school is that students are presented with an introduction to what AM can do for the chemical industries and some hands-on experience on the design, the printing process and to get a flavour of what has already started in different fields. We expect the participation of Master Students and PhD students related to chemistry and chemical, biological and environmental engineering.

The expected number of participants is up to 30 students. The event will take place in Prague at ICPF facilities in the end of August 2018. The programme can be found on PRINTCR3DIT project webpage (here).

5. Syllabus for 3D printing subject at the university

This course provides basic summary of state-of-the-art in 3D printing with focus on the field of chemical engineering applications. The course is divided into theoretical and practical parts. In the theoretical part, students will learn basics of 3D printing technologies, the properties of used materials and the potential of utilization of 3D printing in chemical engineering, with focus on fabrication of structured devices and micro- or milli-reactors. Special attention will be paid to the practical part of the course, which is focused on demonstration of 3D modelling software (CAD), preparing a drawing of their own microreactor and printing, that will serve for a demonstration case in chemical engineering applications chosen according to the student's expertise.
This course is based on fundamentals of natural sciences, such as chemistry, physics and biology.

5.1. Course overview:

Theoretical part:

- Introduction: What is 3D printing?
  - Historical background, important milestones
  - Main differences between 3D printing and other manufacturing techniques – e.g. injection moulding (advantages, disadvantages)
  - Overview of typical usage (personalized production, fast prototyping, costs in relation with production size)
  - Current trends and applications of 3D printing technologies
    - automotive industry, architecture, medicine, dental medicine, bijouterie/jewellery, domestic use
- 3D printing technologies overview, key characteristics, features
  - Common materials used for 3D printing
  - Fused Deposition Modelling (FDM)
  - Stereolithography (SLA, SL)
  - Selective Laser Sintering (SLS)
    - metals, ceramics, plastics
  - Digital Light Processing (DLP)
  - MultiJet printers
- Basics of flow-through microreactors, their features and summary of practical usage in specific technologies
- Heat, mass and momentum transport in microreactors
- Benefit of 3D printing technology for micro- or microstructured reactor fabrication

Practical part:

- Working with 3D modelling software (CAD, free software version will be preferred)
- Preparation of 3D design of a microreactor according to previously chosen application
- Adjustment of 3D design for 3D printer (orientation, building of supports, slicing into layers)
- Printing of a microreactor on a 3D printer, removal and processing of a prototype
- Testing of a printed microreactor to study the following phenomena: heat, mass and momentum transport, kinetics of chemical reactions, mixing, residence time distribution, etc.

6. Examples of 3D printing practical trainings

6.1. Static mixer for decolorization reaction

Aims of demonstration:

- Introduction of the possibility of 3D printing in chemical engineering
- Introduction of the used system, reactor, encountered problems during design of the reactor
- Demonstrate the function of 3D printed continuous reactor and become familiar with spectrometric on-line measurements
- Evaluate the experimental data, determination of reaction rate and kinetic constant

List of chemicals used in the experiment:

- Crystal violet (hexamethyl pararosaniline chloride – $C_{25}N_3H_{30}Cl$ – CAS number: 548-62-9, CV), H302, H318, H351, H410 
- Sodium hydroxide – NaOH – CAS number: 1310-73-2, H314 , H290
- Distilled water
- Ethanol (cleaning purposes), H225, H319

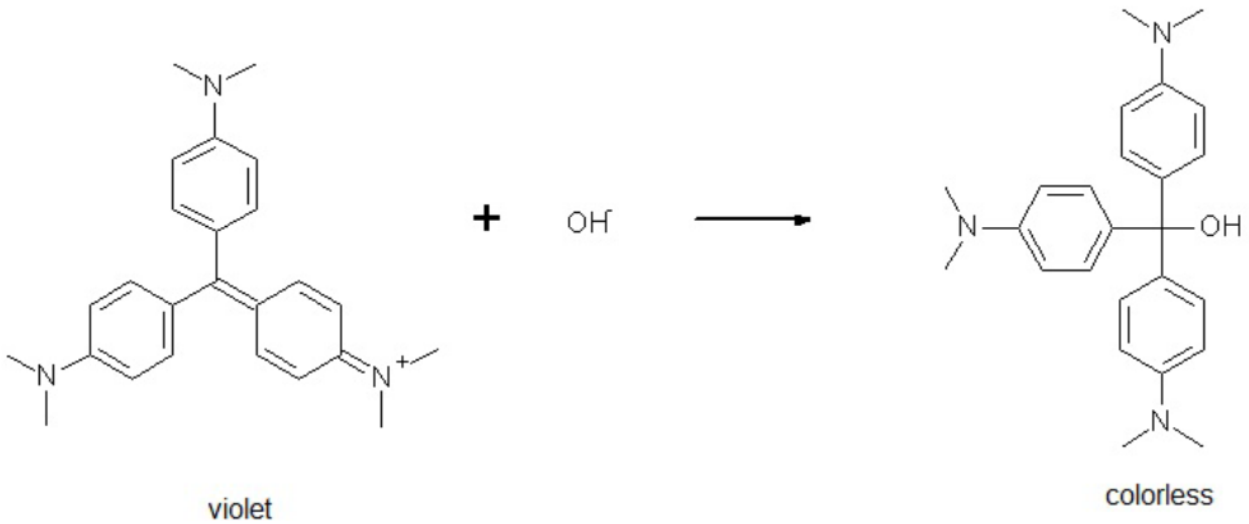


Figure 17 Scheme of the crystal violet reaction with NaOH

Solution concentrations:

- $5 \cdot 10^{-4}$ M CV
- 0.01 M NaOH

Experimental part:

- Measurement of the crystal violet absorption in the range of 470 – 650 nm (592 nm peak)
- Calibration of a spectrometer with distilled water and crystal violet solutions of known concentration
- Absorbance measurement under different flow conditions

Conducting the experiment:

- Switch on all computers and halogen lamp from the spectrometer (NOTE: halogen lamp need min 30 min to heat up before the measurements)

- Write down the time when you switch on the lamp
- Start the programs for controlling the pumps and spectrometer
- Prepare the folders for saving the measurements
- Check if bubbles are in the system. If yes, flush the system with high liquid flowrate (20 ml/min)
- Set the flow rate value on both pumps to 5 ml/min and wait until the flow is steady
- Test the spectrometer baseline with distilled or deionized water
- Fill the glasses with Crystal Violet (CV) and NaOH
- Blue pump → CV
- Green pump → NaOH
- Set up the flow rate values and wait until the flow is steady

Start the measurement and recording

Table of sample names and example of experimental conditions (3x repetition each):

NAME OF SAMPLE	CV/NaOH RATIO	FLOW RATES
PT3D_02_A_01, ..02, 03	1:1	1 ml/min CV + 1 ml/min NaOH
PT3D_02_B_01, ..02, 03	1:1	3.5 ml/min CV + 3.5 ml/min NaOH
PT3D_02_C_01, ..02, 03	1:1	5 ml/min CV + 5 ml/min NaOH
PT3D_02_D_01, ..02, 03	1:1	7.5 ml/min CV + 7.5 ml/min NaOH
PT3D_02_E_01, ..02, 03	1:1	10 ml/min CV + 10 ml/min NaOH

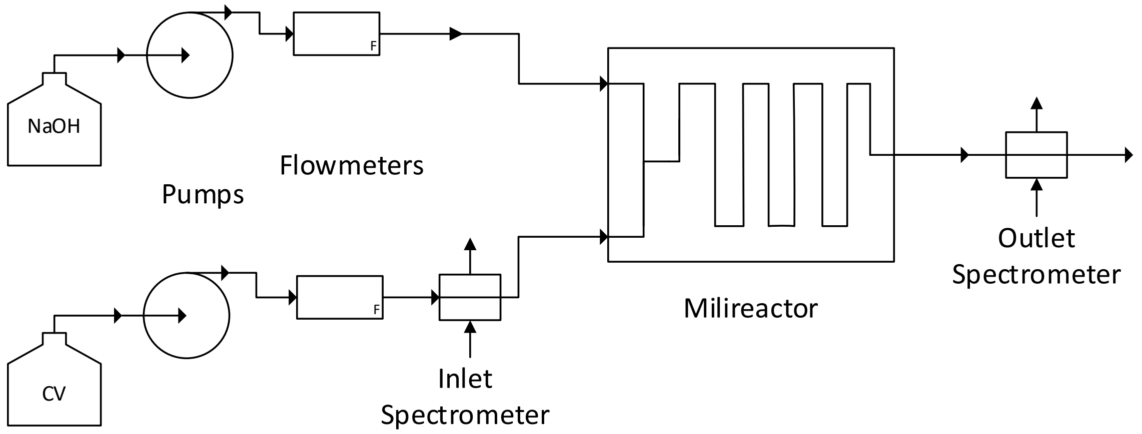


Figure 18 Scheme of the setup for crystal violet decolorization reaction

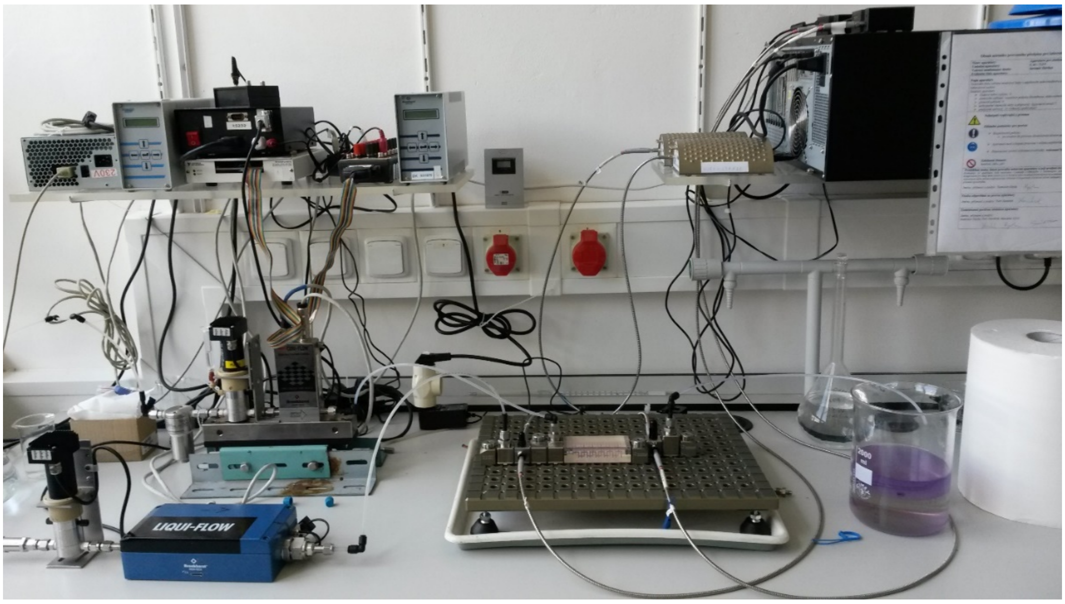


Figure 19 Experimental setup for crystal violet decolorization reaction

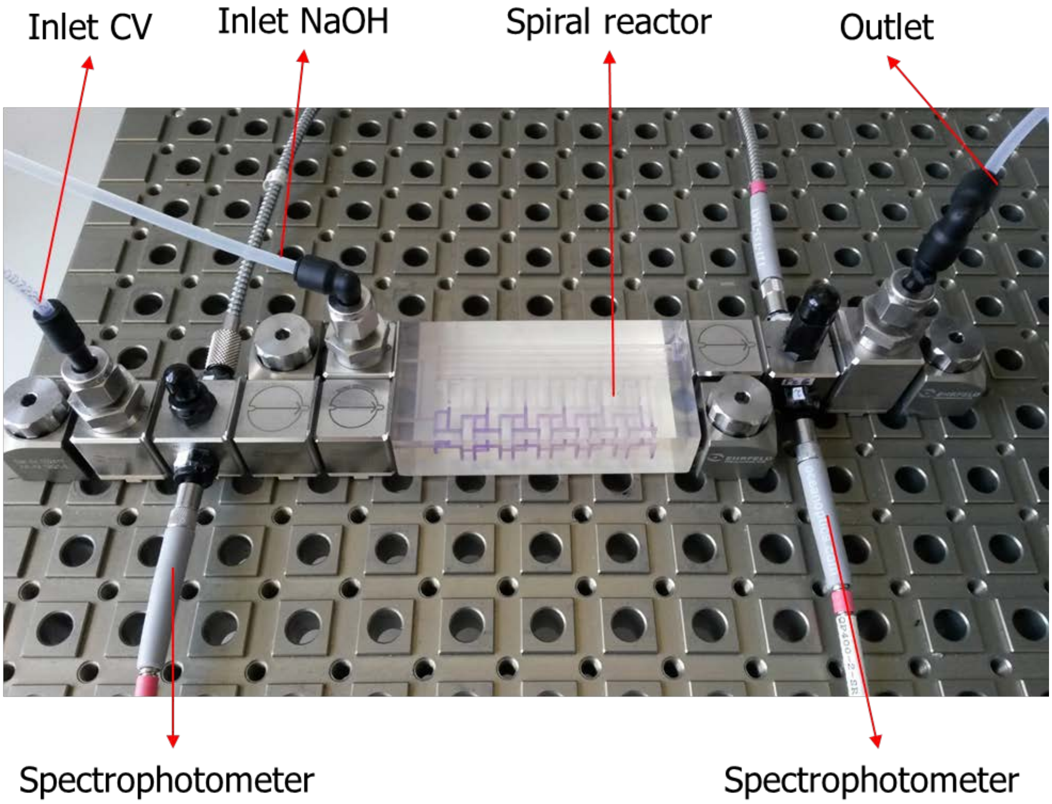


Figure 20 Detail of the 3D printed reactor connection

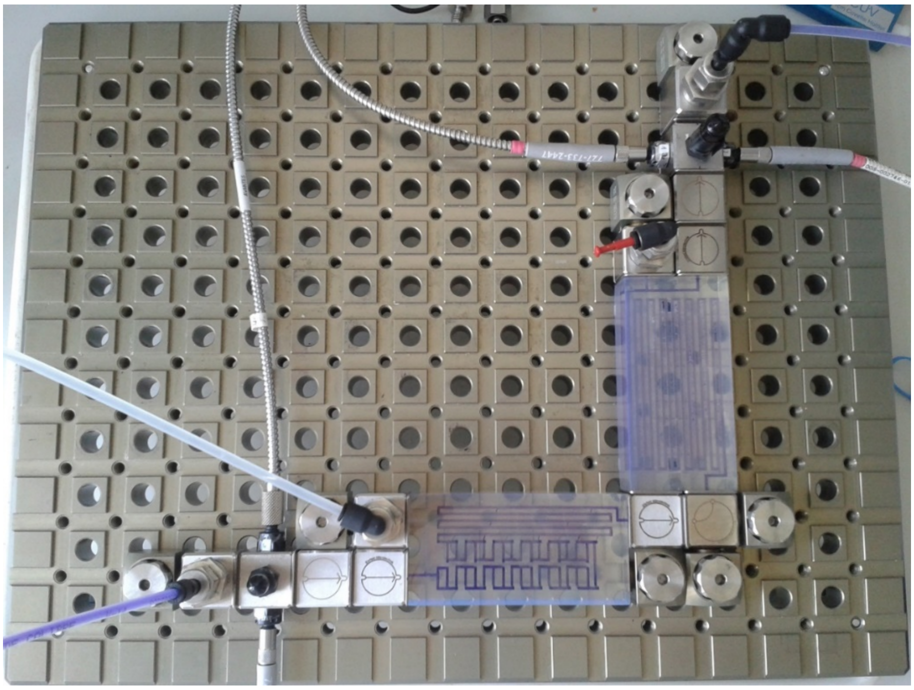


Figure 21 Base plate with the 3D printed reactors with static mixers and residence time loop

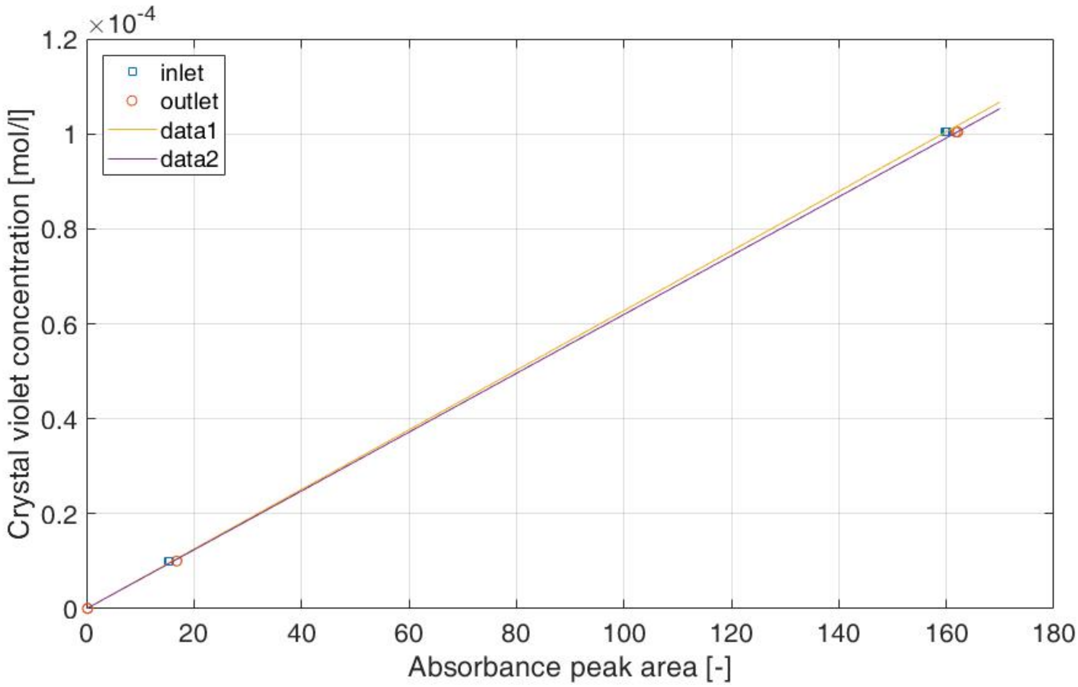


Figure 22 Calibration curve for crystal violet, calibration constants: Inlet: a = 6.2774 x10^{-7}, Outlet: a = 6.1961x10^{-7}

6.2. Pressure drop measurements with 3D printed structures

Aim: characterize the 3D printed structures with regard to pressure drop and compare them with conventional support shapes

Pressure drop is an important operating parameter of industrial units. Pressure drop as low as possible is often required to minimize the operating costs. On the other hand, some pressure drop is necessary to ensure for proper fluid distribution across the reactor cross section and enhance mixing of flowing phases. The 3D printing brings high potential of tailoring the shape of reactor filling with respect to the target flow conditions and fluid properties.

a) b) c)

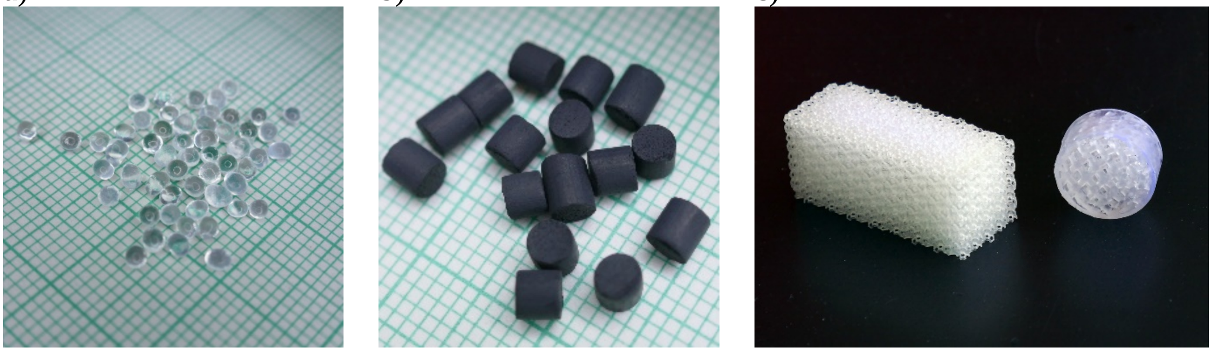
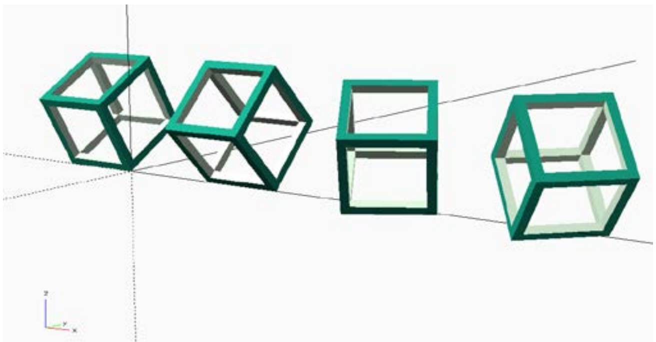


Table 1 Conventional shapes for catalyst supports: spheres (a), cylinders (b), and 3D printed structures (c)

Objective:

The objective of this task is to generate a parametric set of few 3D printed structures, that vary in a selected parameter (porosity, strut diameter, inclination angle or cell size) in a way that allow to study the effect of the selected parameter individually (see Figure 23).



(a)

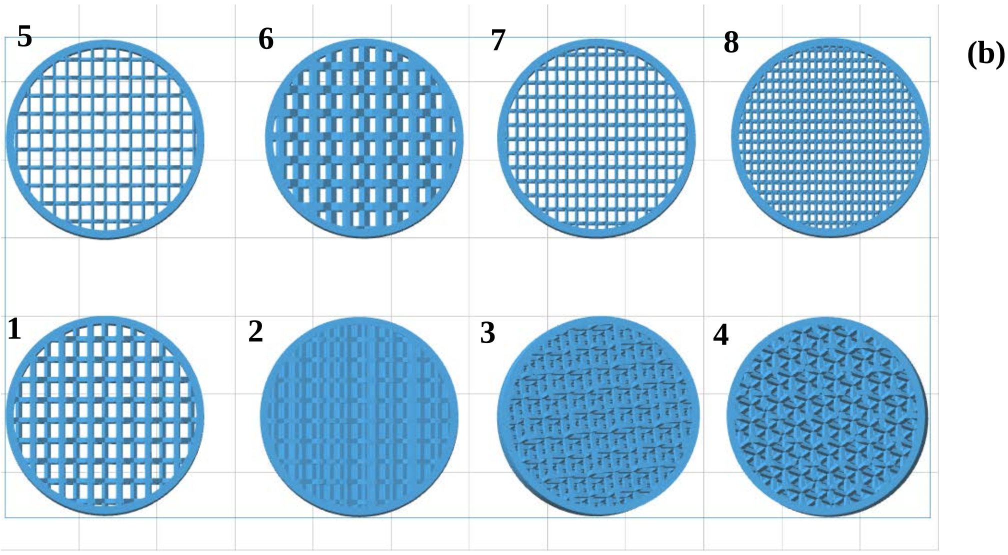


Figure 23 Angular rotation of the cubic cell used in this work and (b) orientation in the 3D printing software of the different foams produced.

Description of the laboratory training:

Perform a measurement of a one-phase pressure drop over the bed consisting of 3D printed structure. The examined parameter will be the effect of gas flowrate in relation to 3D structure geometrical properties. The measured pressure drop can be then correlated by Re number and Ergun equation and compared to conventional shapes or literature data.

Test parameters:

Fluid properties: viscosity, density, surface tension, flow rate.

3D structure properties: porosity, strut diameter, cell size, cell orientation with respect to flow direction, structure topology (Kelvin cell, Whaire-Pellan cell, …)

Schematics:

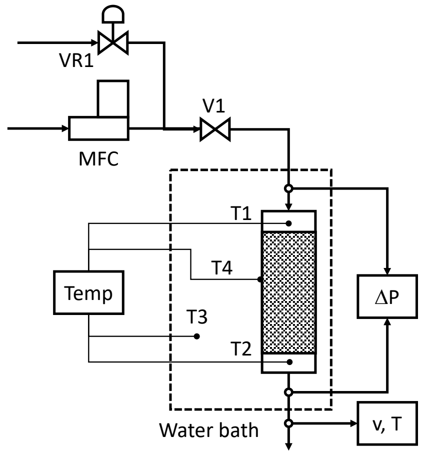


Figure 24 Equipment for pressure drop and heat transfer measuremets. Terminology: MFC: mass flow controller; v, T: velocity and temperature measurement; V1: on-off valve; VR1: needle valve; ΔP: differential pressure meter.

3D printing technology:
FDM or SLA printer for polymers

Equipment:
Supply of pressurized gas, mass flow controller for gas or gas rotameter, tube of a sufficient length (0.5 – 1.0) m as a reactor, one differential and / or two absolute pressure transducers.
The unit can be upgraded using a thermostatic bath and temperature probes for measurement of heat transfer coefficients.

Reference: Bastos Rebelo, N. F.; Andreassen, K. A.; Suarez Ríos, L. I.; Piquero Camblor, J. C.; Zander, H.-J.; Grande, C. A. Pressure drop and heat transfer properties of cubic iso-reticular foams. Chemical Engineering and Processing - Process Intensification 2018, 127, 36.

6.3. Droplet generation – Application of 3D printed microfluidic cell (MFC)

Aim:

Generate stable emulsions of Water/Oil or Oil/Water with well-defined droplet size and narrow particle size distribution (PSD).

Objective:

Oil/Water or Water/Oil emulsions have wide range of applications in many fields of every day human life. Production of emulsions with well-defined droplet size in laminar flow conditions brings possibility to work with materials predisposed to structure damage when high shear rates are applied. Encapsulation of various active pharmaceutical substances could be typical industrial application of such process.

Description of a laboratory test:
Preparation of Water/Oil emulsions:

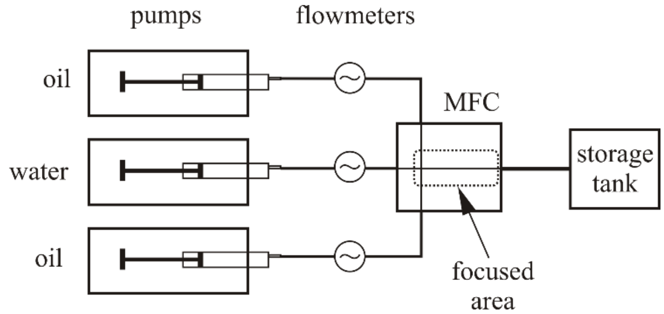
Water and oil phases are inserted into the syringe and allocated into the syringe pump. Oil phase is split to the two lines and connected to the side inlets of the MFC. Water phase is connected to the central inlet of the MFC. Droplets of defined sizes can be produced by the variation of both flow rates.

Engineering information available from the test are: droplet size as a function of flow rate, droplet size distribution as a function of flow rate. Results can be correlated by Re, We, Eo, and St when frequency of surface oscillation is detected.

Test parameters:

Water phase: viscosity, density, salinity, surface tension, flow rate.
Oil phase: viscosity, density, salinity, surface tension, flow rate.

Schematics:



3D printing technology:

FDM printer, Ultimaker MK2 brand, material: transparent polyamide
SLA printer with a transparent resin

Equipment:

3D printed microfluidic chip, 3D printed frame for the chip, 3x single channel syringe pump, 3x flow meters, digital microscope with high speed recording (sufficient speed 60 fps), and image processing software

a) b)

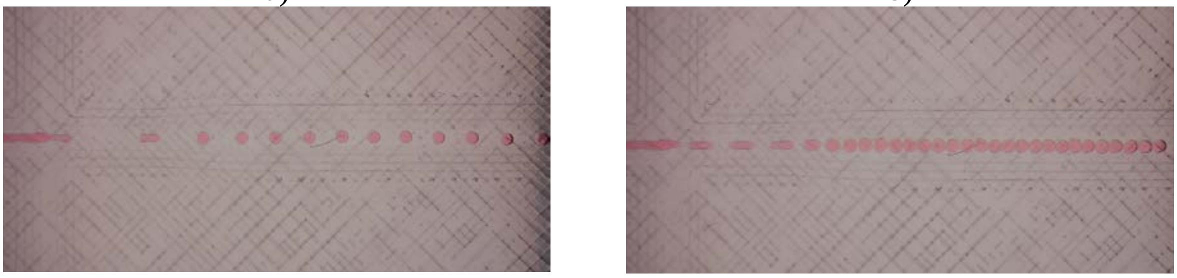


Figure 25 Focused area of MFC at low flow rate a) and high flow rate b) conditions.

a) b)

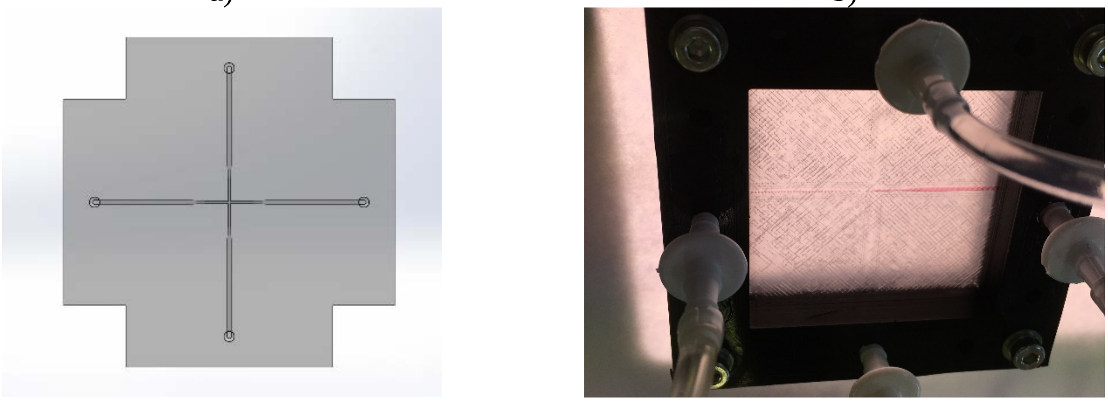


Figure 26 MFC geometry a) and detail with pump connections b).

a) b)

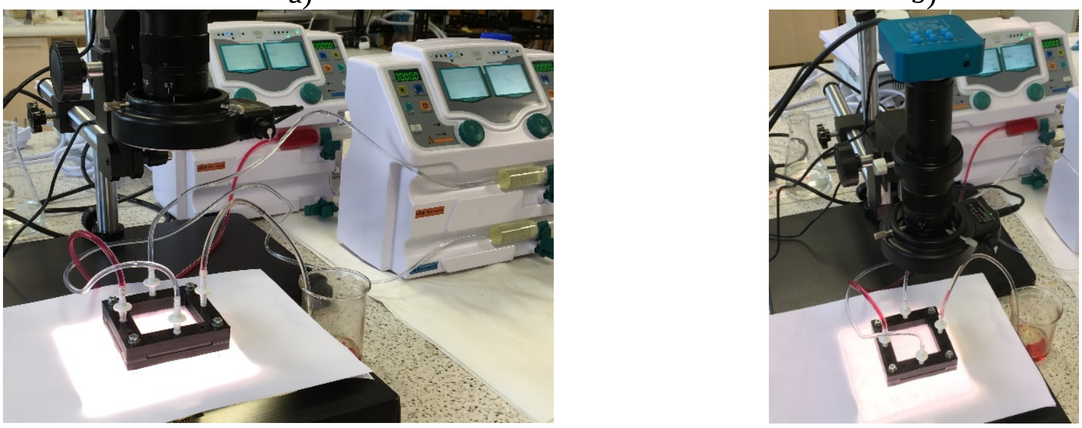


Figure 27 Overall view of experimental station a), high speed microscope b).

7. Conclusions

The performed survey at universities reported here has shown that the 3D printing technologies are being already implemented as a part of engineering educational programmes, but the cases are rather exceptional. Despite the interest of students and awareness by university professors, its wider implementation faces the main barriers in terms costs and missing educational materials. It is obvious that even today the FDM machines are affordable and with further development even advanced 3D printing technologies (such as SLA) becomes affordable for universities to equip their lab with sufficient number of devices. Therefore, more applications of 3D printing in education can be expected in the near future. For this reason, the course materials and practical examples that are part of this report can act as a support or source of inspiration for students and university professors that are interested in 3D printing technologies. The first summer school of Additive manufacturing that will take place in August 2018 in Prague can be a one of such first trainings.

Acknowledgement

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