Photo-Induced Copper-Mediated Acrylate Polymerization in Continuous-Flow Reactors

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Abstract

The synthetic scope of photo-induced copper mediated polymerization (photoCMP) in continuous flow reactors further explored. A series of monomers, namely methyl (MA), ethyl (EA), *n*-butyl (*n*BA), 2-hydroxyethyl (HEA) and di(ethylene glycol) ethyl ether (DEGA) acrylate are investigated, all showing high livingness (dispersity in the range of 1.1 and linear first order kinetics) in the polymerizations and high conversions within 20 min reaction time. Next to the commonly used solvent DMSO, also water/ethanol mixture can be used as greener alternative, without any loss in reaction control. Upscaling the reactor from 2 to 16 mL allows for production of over 200 g of high-definition material (3000 g·mol^{-1}, 1.1 dispersity) in overnight operation (18 h), demonstrating that the photoprocess can be run under very stable conditions even for extended

reaction times. Also, coupling of reactors is possible, which affords for block copolymers in a single reaction step.

Introduction

Photochemistry is an old branch of chemistry, but has to date only played a minor role in materials synthesis outside of curing processes and some highly specific applications in natural product synthesis, despite the enormous potential of photoreactions with regards to reaction efficiencies and in principle advantageous economy and ecology of light-induced reactions. With the increasing popularity of continuous flow reactors, photochemistry regained focus of academic as well as industrial research.[1] Usage of photochemically triggered reactions allows for reaction pathways and mechanisms which are not or only indirectly accessible with thermally induced reactions. Yet, the main drawback of light induced reactions was so far always the issues occurring with respect to scalability. Due to the Beer-Lambert´s law, light gradients develop in any photoreaction carried out in batch due to successive light absorption with increasing optical pathlength, penalizing the efficiency of the reaction in that the desired chemical transformations mostly only take place at the reactor wall whereas the bulk of the reaction mixture remains a dead volume.[2] This problem might be negligible on small scale lab experiments but becomes rapidly significant in reaction upscaling, already at an intermediate laboratory scale. Continuous flow reactors, however, can give an essential advantage and be a *game changer* for application of photochemistry in (scalable) synthesis. In continuous flow reactors reactions are mostly performed in thin reaction channels which guarantee normally good heat transfer, but at the same time also

allow for avoidance of light intensity gradients.[2] Continuous flow reactors in laboratories are often made out of fluoropolymer tubing with a diameter of less than 2 mm.[3] With average extinction coefficients, these diameters are small enough to not cause significant radial light gradients, and hence the problems with upscaling of photoreactions are entirely avoided.[2] Despite the small diameters, larger reactor volumes are still easily achieved by increasing the tubing or via reactor parallelization.[4]

Within the realm of polymer chemistry, the large potential of using (photo)flow reactors for the synthesis of precision polymer materials has only recently emerged.[2] Precision polymer materials are commonly synthesized via living polymerization techniques, more specifically via reversible deactivation radical polymerization (RDRP) methods. RDRP gives access to polymers with high definition, narrow dispersity and sophisticated control over the macromolecular architecture, and already for thermal RDRP, the advantage of using flow reactions has been demonstrated.[5] The most applied RDRP methods are the so-called reversible addition-fragmentation chain transfer polymerization (RAFT)[6], nitroxide mediated polymerization (NMP)[7] and transition metal mediated polymerization[8] such as atom transfer radical polymerization (ATRP)[9] and single electron transfer living radical polymerization (SET-LRP).[10] In the past years, for all main RDRP methods also photo-induced processes have been discovered and investigated.[11] Successful photo-induced transition metal mediated polymerizations are reported in literature and a broad range of catalysts has been used, with cobalt[12], iron[13], irridium[14] and copper[15] being the most important examples. Junkers and coworkers described first the combination of photo-induced copper-mediated polymerization (photoCMP) and continuous flow reactors, based on the batch concept introduced by the Haddleton group.[15a] First, only the polymerization of acrylates[16] was studied, followed by the synthesis of poly(methacrylates) and methacrylate – acrylate block copolymers in

flow.[17] Next to such linear block copolymer structures, recently also the (flow) synthesis of star shaped multiblock copolymers via photoCMP was investigated.[18] As mentioned above, photoflow polymerizations are also reported for cobalt[19] and iridium[20] mediated reactions. PhotoCMP was also successfully applied for grafting on silicon surfaces[21] or to make sequence defined oligomers with biological precision, albeit not in continuous flow.[22] Additionally, two groups reported lately on successful photo-induced RAFT polymerization in flow reactors.[23] Baeten et al used a photoflow microreactor for inline UV-modification of phosphoesters via a thiol-ene reaction.[24]

While photoRDRP[25] has very interesting features such as enhanced structural purity and ability for spatiotemporal control, its potential as a pure synthetic tool (where spatial control plays no major role) is to date vastly unexplored, also owing to the scalability gap outlined above. In here, we extend our initial proof of principle work on photoCMP in continuous flow reactors[16] and demonstrate the high versatility of the technique. Continuous flow synthesis is demonstrated for a range of (acrylic) monomers, under variation of chain length, and reaction solvent in order to reach greener reaction conditions (note that classical photoCMP required DMSO as solvent, which is certainly not sustainable with respect to commercial application). In a final step, also a two-stage reactor for diblock copolymer synthesis is described, alongside a first upscale to higher laboratory scale synthesis.

Experimental

Materials:

Ethyl 2-bromoisbutyrate (EBiB, Alfa Aesar, 98+%), copper (II) bromide ($CuBr_2$, Sigma-Aldrich, 99%), Ethanol (EtOH Merck, pro analysis) and dimethyl sulfoxide (DMSO, Merck, pro analysis) were all used as received. Tris-(2-(dimethylamino)ethyl)amine (Me_6TREN)[26] and 2-Hydroxyethyl 2`-Methyl-2`bromopropionate (HMB)[27] were synthesized following literature procedures. Methyl acrylate (MA, Acros, 99%), ethyl acrylate (EA, Acros, 99.5%), di(ethylene glycol) ethyl ether acrylate (DEGA, TCI, 98%), 2-hydroxyethyl acrylate (HEA, TCI, 95%) and *n*-butyl acrylate (*n*BA, Acros, 99%) were deinhibited over a column of activated basic alumina, prior to use. Additionally 2-hydroxyethyl acrylate (HEA, TCI, 95%) was purified by distillation.

Methods:

^{1}H NMR spectra were recorded in deuterated chloroform applying a pulse delay of 12 s with Oxford Instruments Ltd. NMR spectrometers (300 and 400 MHz).

Analytical **SEC** (Size Exclusion Chromatography) was performed on a Tosoh EcoSEC HLC-8320GPC, comprising an autosampler, a PSS guard column SDV (50 × 7.5 mm), followed by three PSS SDV analytical linear XL (5 µm, 300 × 7.5 mm) columns thermostatted at 40 ^{0}C (column molecular weight range: 1×10^2 to 1×10^6 g mol^{-1}), and a differential refractive index detector (Tosoh EcoSEC RI) using THF as the eluent with a flow rate of 1 mL min^{-1}. Toluene was used as a flow marker. Calibration was performed using linear narrow polystyrene (PS) standards from PSS Laboratories in the range of 470–7.5×10^6 g mol^{-1}. For the analysis the following MHKS parameters were used: MA, EA and HEA α=0.74, K=10.2×10^{-5} dL g^{-1} in THF at 30 ^{0}C[28]; for *n*BA

α=0.70, K=12.2 × 10^{-5} dL g^{-1} in THF at 40 ^{0}C[29] for *n*BA and Polystyrene calibration α=0.714, K=13.63 × 10^{-5} dL g^{-1}, THF 30 ^{0}C at 633 nm for DEGA.[30]

The **continuous photoflow reactors** were built up out of a 4.5 m PFA tubing (Advanced Polymer Tubing GmbH, outer diameter 1/16", inner diameter 0.75 mm, reactor volume 2 mL) wrapped around a Vilbour Lurmant 15 W UV-light tube (λ_{max} = 365 nm). A Syringe pump (Chemyx Fusion 100) was used to inject the reaction solutions into the reactor. The lamp heated the reactions to a temperature between 50 and 55 °C. For the scale up 20.5 m of PFA tubing with an internal diameter of 1 mm (reactor volume 16 mL) was wrapped around the same lamp. Two Knauer Azura HPLC pumps were used to deliver the reaction solutions. In both reactors a static T-mixer (Upchurch Scientific) was employed.

Coupled photoflow reactors For the coupled reactors 2.3 m and 3.5 m PFA tubing (Advanced Polymer Tubing GmbH, outer diameter 1/16", inner diameter 0.75 mm, reactor volume 1 mL respectively 1.5 mL) were wrapped around a 15 W UV-light tube (Vilbour Lurmant, λ_{max} = 365 nm). The reaction solutions were loaded into two NormJect plastic syringes and a Chemyx Fusion 100 syringe pump was used to deliver the solutions. For fast reaction solution mixing a static mixer (Upchurch Scientific) was added in the lines before entering the reactor. The exit of the first reactor was coupled to a second static mixer. In this mixer also second monomer solution was supplied via a NormJect syringe and a Chemyx pump. The lamp created a reaction temperature between 50 and 55 °C.

General polymerization procedure using the continuous photoflow reactor. EBiB (1 eq.), $CuBr_2$ (0.02 eq.) and Me_6TREN (0.12 eq.) were mixed in a 20 mL amber volumetric flask which was filled up with DMSO. 20 mL monomer (25 – 500eq.) was filled into a separate amber volumetric flask and both were purged with nitrogen gas for approximately 15 minutes. The

solutions were transferred into Normject plastic syringes and placed in the syringe pump. Different reaction times were screened via adjusting the flow rate (between 0.025 and 1 mL min^{-1}).

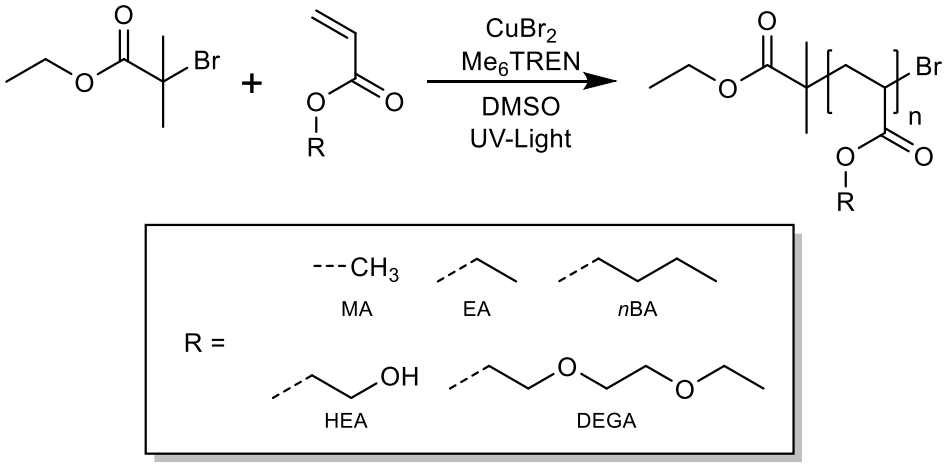
Polymerization of DEGA in a water/ethanol mixture. Before purging for 15 minutes with nitrogen gas one amber volumetric flask was filled with DEGA (25 – 100 eq.) and another one with HMB (1 eq.), $CuBr_2$ (0.02 eq.) and Me_6TREN (0.12 eq.) and a 50/50 vol% H_2O/EtOH mixture. The oxygen free solutions were loaded into two Normject syringes and a syringe pump was used to deliver the solutions into the reactor. By changing the flow rates several reaction times were screened.

One step chain extension of DEGA in a water/ethanol mixture. In a 10 mL amber volumetric flask 0.42 g (2.16 mmol, 1 eq.) HMB, 0.01 g (0.04 mmol, 0.02 eq.) $CuBr_2$ and 0.06 g (0.26 mmol, 0.12 eq.) Me_6TREN were dissolve in a 50/50 vol% H_2O/EtOH mixture. This solution as well as 10 mL DEGA were purged for 10 minutes with nitrogen and transferred into two syringes. For second monomer addition 5 mL DEGA was mixed with 5 mL 50/50 vol% H_2O/EtOH mixture, purged with N_2 for 10 minutes and loaded into a syringe.

Results and Discussions

In our previous studies on photoCMP in flow we had largely focused on methyl acrylate, MA, (and to some extend methyl methacrylate, MMA) as the simplest member of the (meth)acrylate families, in order to provide a proof of concept study. While reactions with MA and MMA were largely successful and convincingly demonstrated the superiority of using flow reactors for photoRDRP, only relatively simple polymers from a materials point of view were in this way generated. Testing which other monomers are suitable for photoflow is hence almost obligatory, also in order to establish in how far the to date observed kinetics may also hold if the polarity of the ester side chain is changed.

Thus, a broad range of different acrylic monomers were polymerized via photoCMP in a continuous flow reactor. As representatives for linear hydrophobic monomers methyl (MA), ethyl (EA) and *n*-butyl acrylate (*n*BA) were chosen. Comparison of this short series of monomers helps to reveal the influence of the ester size on the polymerization performance. As more polar counterparts 2-hydroxyethyl acrylate (HEA) and di(ethylene glycol) ethyl ether acrylate (DEGA) were tested, to cover also synthetically more interesting materials (see Scheme 1 for structures of all monomers). All polymers were synthesized in a relatively simple, but yet effciient continuous



Scheme 1 Reaction scheme for photo-induced copper-mediated polymerization (photoCMP) and the used acrylate monomers.

tubular flow reactor consisting of PFA tubing wraped around a UV-light tube and a syringe pump to deliver the reaction solutions. In line with our previous study, all polymerizations were performed in DMSO between 50 and 55 °C (it must be noted that the temperature is a consequence of heat-up of the light source during reactor operation) with reaction times up to 20 minutes. In principle, longer reaction times could be used, but in order to allow for reasonable space-time yields, 20 min was chosen as an aribtrary maximum reaction time. As initiator EBiB was used, in a ratio of 1:0.02:0.12 for [EBiB]:[$CuBr_2$]:[Me_6TREN]. All components were dissolved in solvent, degassed and transfered into a plastic syringe. A second syringe was filled with degassed monomer with ratios of 25 or 45 to initiator and in a volumtric solvent ratio of 1:1. Both solutions were mixed right before entering the reactor in a static T-mixer. All polymerizations show high reaction rates with monomer conversions between 76 and 94 % within 20 minutes reaction time (see Table 1 for details). As important as high reaction rates for RDRP are, it is even more crucial to have a good controll over the reaction and the length of the obtained polymer. Hence, linear first order kinetic plots with respect to monomer concentartion must be observed (demonstrating a constant radical concetration and hence absence of radical termination), alongside linear growth of the polymer material. For all polymers the measured number average molecular weights are in good agreement with the theoreticaly calculated values (Table 1). Dispersities are around 1.1 indicating rather narrow molecular weight distributions (MWD) and a high control over the polymerizations. The narrow distributions thereby do not only indicate good control, but also underpin that the residence time distribution (RTD) of the polymer is narrow as well, since axial diffusion would increase the RTD and hence the overall dispersity of the resulting polymer. Only *n*BA is associated with a slighly increased dispersity of 1.2, which may, however, still be regarded as in line with the

other results. A similarly deviating behaviour was reported previously for photoCMP polymerization of *n*BA in batch.[15a]

Table 1 Overview over the obtained polymers from photoCMP in a continuous flow reactor for different acrylate monomers after 20 minutes reaction time.

	monomer	In:$CuBr_2$:Li:M	conversion [%]	$M_{n,theo}$ [g mol^{-1}]	$M_{n,GPC}$ [g mol^{-1}]	$Đ$
1	MA	1:0.02:0.12:45	77	3100	2600	1.12
2	EA	1:0.02:0.12:45	76	3600	2200	1.11
3	*n*BA	1:0.02:0.12:25	90	3000	3200	1.23
4	HEA	1:0.02:0.12:25	94	2900	1200	1.07
5	DEGA	1:0.02:0.12:25	83	4000	3000	1.10

The kinetic first-order plots for all polymerizations show the required linear behavior (Figure 1), again underpinning the high level of control over the chain growth that is reached. Only few side reactions seemingly occur, and termination and radical transfer play no significant role in the reaction. Yet, different slopes are observed in the plots, and a significant rate increase is observed for HEA, which can likely be correlated to a faster propagation of this monomer in highly polar media compared to the other monomers.

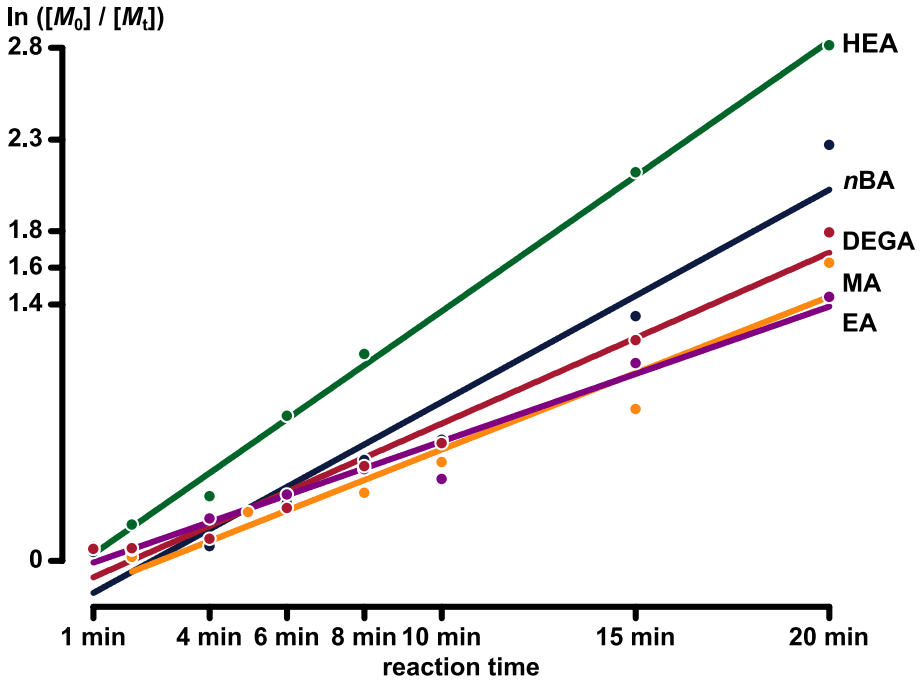


Figure 1 Kinetic first-order plots for the photoCMP polymerization in DMSO of different acrylates in a continuous tubular photoflow reactor.

Increasing Chain Length

After showing the wide applicability of photoCMP with different acrylate monomers the limits of the reaction concerning polymer chain length was tested. Increasing chain length is associated with different problems. Higher molecular weight material causes higher viscosities, and hence leads to increased pressure drops and eventually clogging of the reactor system. At the same time – characteristic for photoCMP – a lower polymerization rate must be expected when the initiator concentration is lowered (less bromine available for chain initiation). To our best knowledge until today only degrees of polymerization (DP) up to 100 have been reported in literature for photoCMP flow processes. In here, the DP is increased step wise, which corresponds to molecular weights in the range of 20 000 g/mol. Target degrees of polymerizations were set to 500, however, due to limitations in the reaction rate (see above), maximum DPs reached in practice were about 250. Nevertheless, for most applications of high-precision polymer materials (i.e. biomedical use)

as described herein, no longer polymer chains are required. The polymerizations were again performed in a continuous tubular reactor equipped with a 15 Watt UV-light tube. For increasing targeted DP an increase in number average molecular weight was observed, even if monomer conversions reached within 20 minutes decreased in accordance to the lowered initiation rate. In Figure 2 the MWDs of polymers obtained after polymerizations of 20 minutes are given, depicting a clear shift to higher molecular weights with increasing targeted DPs. Interestingly, while a rate reduction is observed, no quality loss in the product is seen, and all polymers are constant within error limits with respect to dispersity. All molecular weights obtained are all in good agreement to calculated theoretical values, when monomer conversion is taken into account.

Table 2 Target degree of polymerization (at hypothetical full monomer conversion), conversion after 20 min reaction timer and theoretical and experimental number-average molecular weight and dispersity for a series of methyl acrylate polymerizations.

	DP	**conversion [%]**	$M_{n,theo}$ **[g mol^{-1}]**	$M_{n,GPC}$ **[g mol^{-1}]**	$Đ$
1	45	77	3100	2600	1.12
6	100	58	5100	3700	1.13
7	150	77	10000	9300	1.10
8	200	64	11000	8800	1.18
9	300	55	14300	12600	1.15
10	400	63	21800	19900	1.14
11	500	49	21200	16400	1.14

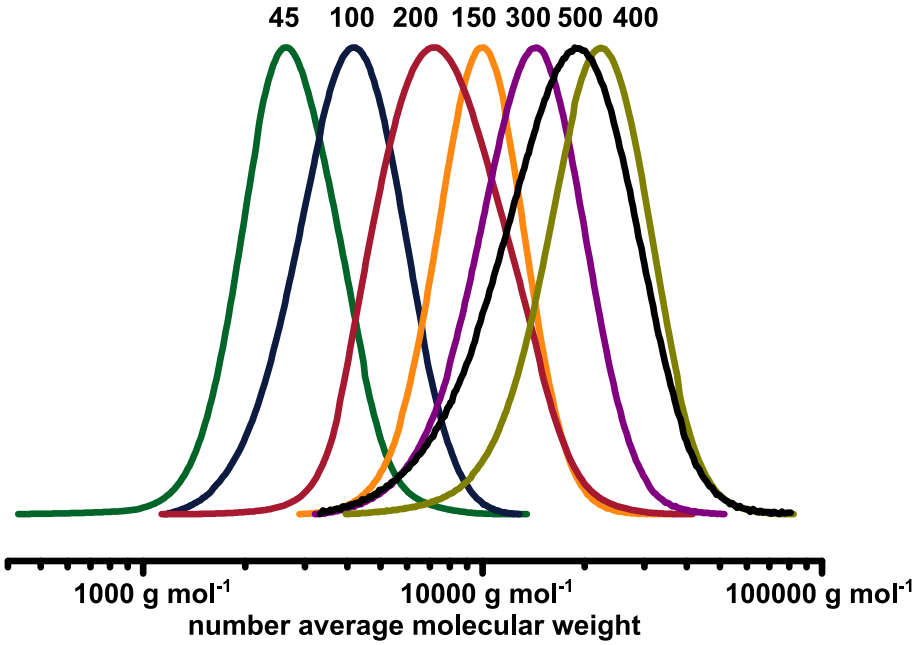
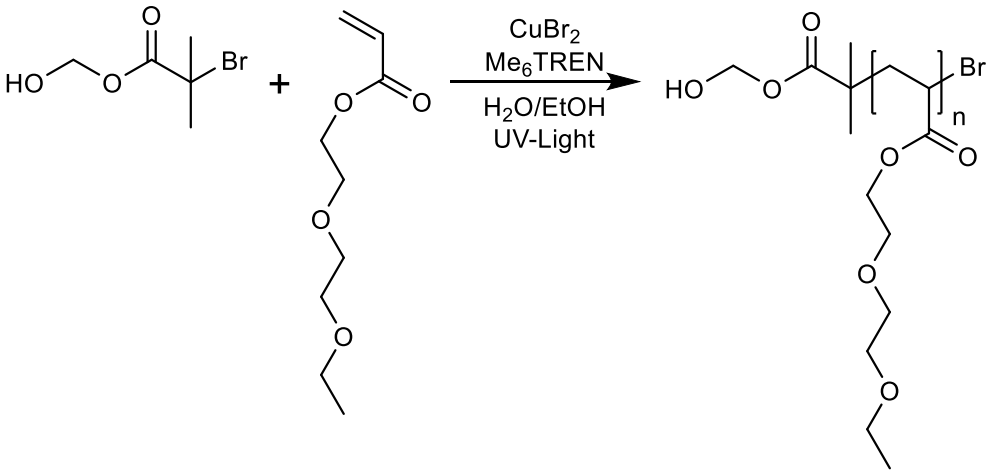


Figure 2 Molecular weight distributions for polymers made in continuous flow photoCMP of methyl acrylate under variation of the initiator concentration in order to produce materials with different target molecular weight.

photoCMP using H_2O/EtOH as solvent

photoCMP is routinely carried out in DMSO. Yet, other polar solvents are equally suitable, with alcohol/water mixtures being a benign alternative. It should be noted that ideally polymerizations



Scheme 2 Reaction scheme for the synthesis of pDEGA in H_2O/EtOH (50:50 vol%) via photoCMP.

should be carried out in pure water, however, this has to date also for batch reactions been shown to lead to a loss of control, which is a somewhat surprising result as SET-LRP reactions are in principle well compatible with water.[31] In here, we tested if the photoCMP reaction is suitable for flow processing when being carried out in a 50:50 vol% H_2O/Ethanol solvent mixture. For these tests, the water soluble monomer DEGA was used. The initiator was changed from EBiB to the more hydrophilic HMB (Scheme 2). For the polymerization different chain length are targeted to show again the robustness of the system. Reactions with target DPs of 25, 50 and 100 were carried out, reaching almost quantitative conversion of monomer in all cases within 20 min reaction time (Table 3). In comparison to the polymerization of DEGA in DMSO (see Table 1, line 5) the conversion increased by 15 %, which may again be attributed to polar effects on the propagation rate of the monomer. However, the reaction in DMSO provided material with slightly better dispersity compared to reaction carried out in H_2O/EtOH.

Table 3 Number-average molecular weights, dispersities and conversion for the polymerization of DEGA via photoCMP in 50/50 vol% H_2O/EtOH in a photoflow reactor.

	DP	**conversion [%]**	$M_{n,theo}$ **[g mol^{-1}]**	$M_{n,GPC}$ **[g mol^{-1}]**	$Đ$
12	25	98	4800	5600	1.22
13	50	98	9400	6900	1.23
14	100	92	17500	12800	1.17

Number-average molecular weights up to 13 000 g·mol^{-1} within 20 minutes reaction time were reached (Figure 3). Closer inspection of the kinetics reveal that 20 minutes is in these cases almost not necessary as conversions above 90 % are observed already after 10 min, which in many cases

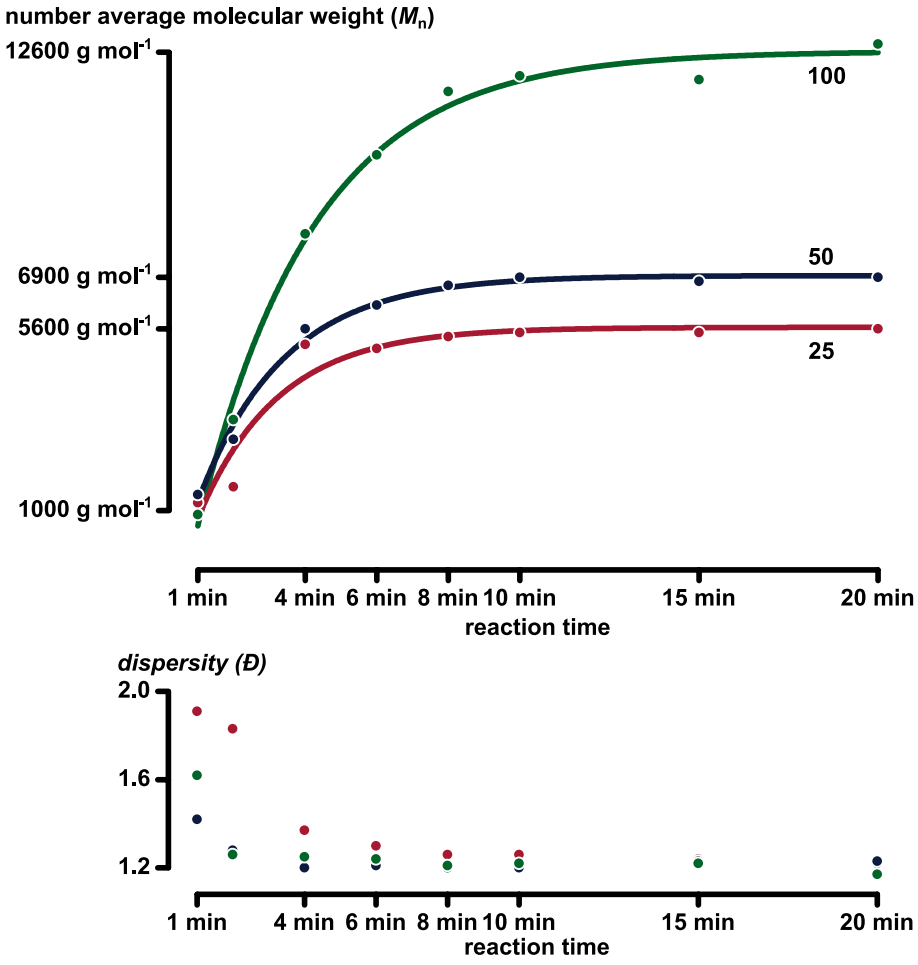


Figure 3 Evolution of number average molecular weights and dispersities of pDEGA in photoCMP using a 50/50 vol% H_2O/EtOH mixture as solvent for various target DP.

might be regarded as sufficient for synthesis purposes. On the other hand, extending the reactor residence time also has no destructive influence on the reaction outcome. Dispersities remain widely constant, indicating that the polymerization comes to a mere halt rather than entering side reactions when monomer concentration diminishes (as is often observed for other RDRP techniques).

Upscaling of photoCMP in continuous flow

As described, the main advantage of using continuous flow for photopolymerizations is the scalability of the reaction. When carried out in batch, photoCMP is usually not carried out above the lower gram scale, if not lower. Thus, the ability to go beyond this limitation was tested for the above described flow reactor design. Whereas the above polymerizations were carried out in a 2mL reactor with 0.75 mm inner diameter, a first scale-up was performed by employing PFA tubing with an inner diameter of 1 mm (outer diameter 1/16") and a total internal volume of 16 mL was used. (see right side of Figure 4). Such reactor is still relatively small and can easily be operated in a standard fumecupboard. Two Knauer Azura P2.1S HPLC pumps were used to deliver the two reaction solutions, which were otherwise chosen accordingly to the previous experiments (first solution containing initiator (EBiB, 1 eq.), $CuBr_2$ (0.02 eq.), Me_6TREN (0.12 eq.) and DMSO; second feed was bulk methyl acrylate). Also in this case, a relatively simple static T-mixer was used to combine both feed streams. At a reaction time of 40 min (as shown above, a slightly higher residence time does not harm the product and ensures better conversions) this reactor setup produces roughly 11 g of pMA per hour with a number average molecular weight of 3000 g mol^{-1} and a dispersity of 1.1. Important to note is that if the reaction conditions would change during operation of the reactor (due to fouling, inconsistent mass transport due to the viscous flow), then inevitably a broadening of the molecular weight distribution of the collected material should occur, as variations in residence time will lead to variations in absolute molecular weight as well. The reactor was operated continuously for 18 hours yielding over 200 g of high quality polymer (see Figure 4), still retaining very narrow molecular weight distributions. No further reaction optimization was required to achieve this upscale from the 2 mL to the 16 mL reactor. Further, 200 g of material may for high precision photoCMP polymers be regarded as a very significant

production scale (due to the very high value of these materials), that even in conventional thermal batch polymerizations are not easily reached on laboratory scale.

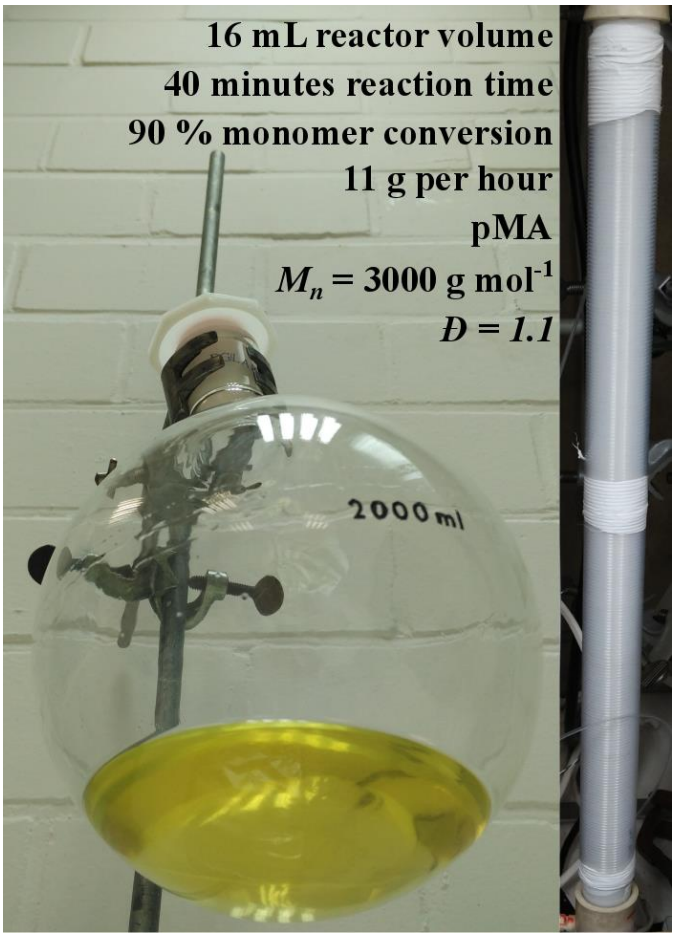


Figure 4 Photo of the tubular flow reactor with an internal volume of 16 mL (right) and the 200 g pMA obtained by collection of product over 18 hour in the same reactor (left).

Thus, scale up of the reaction is indeed simple, and reactor setups that produce 100 or more grams of highly precise polymers per hour should be no significant hurdle, and even larger amounts may only be limited by the available light choice.

Reactor cascade for block copolymer synthesis

The full potential of RDRP reactions unfolds when more complex materials are targeted, by making use of sequential polymerization approaches. By isolation of polymer, followed by mixing with fresh monomer and catalyst, block copolymers become available after reinitiation. Especially when polymers with different solubility and miscibility are used, interesting materials can in this way be quickly synthesized. We had shown before that photoCMP-made block copolymers are available from flow processes, when polymers are isolated after the first reactor stage. The purification between the two reactions makes the full process, however, labor intensive and thus expensive. Using a reactor cascade can solve this problem, as in case almost all monomer is used up in the first reaction stage, no purification is in fact required before addition of fresh monomers. Two serial flow reactors hence give direct access to (multi) block copolymers.[32]

Consequently, the reactor setup was extended by a second stage. In principle, no additional light source is required as the tubing for both stages can conveniently be wrapped around the same light bulb. Two reaction solutions were prepared, degassed and filled in individual plastic syringes. One reaction solution contained the initiator, $CuBr_2$, Me_6TREN and the solvent. The second syringe

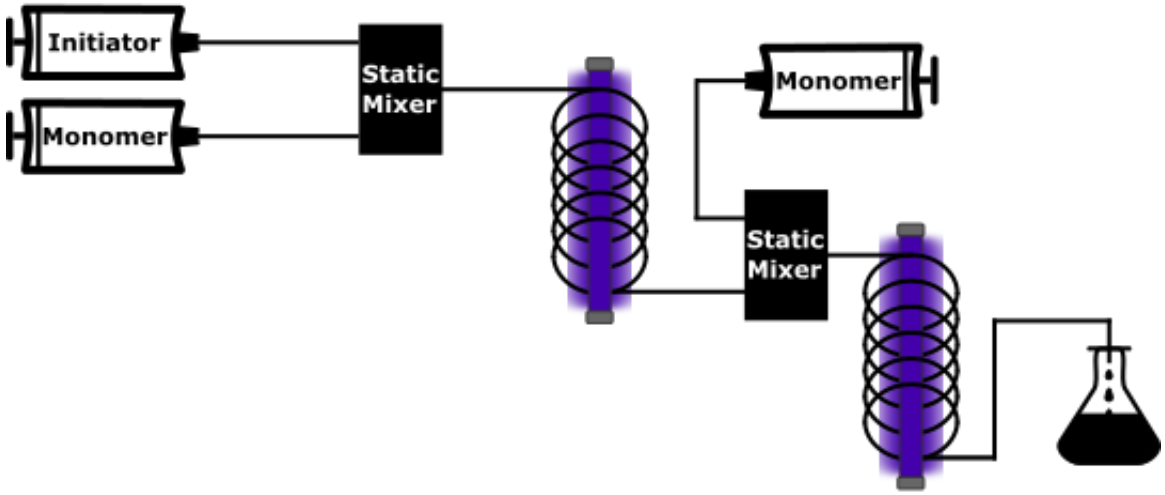


Figure 5 Schematic photoflow reactor setup for the one step synthesis of diblock copolymers.

was used to deliver the first monomer batch (DEGA). Both solutions were mixed in a static mixer before entering the reactor tube which was wrapped around the UV-light tube. The exit of this reactor was connected with a second static mixer where the second monomer solution was added. Dilution is required in the second stage to avoid increasing viscosities with increasing polymer chain length. Polymer samples are collected after the first reactor stage and after passing through both stages. The experimental setup is schematically given in Figure 5. It should be noted that in the present case, DEGA was used for both polymer blocks, hence, no true block copolymer was obtained. Yet, DEGA is a very interesting monomer for amphiphilic block copolymer synthesis, and it is more convenient to chain extend with the same monomer for the sake of simpler polymer analysis (no change in Mark-Houwink parameters). In principle, the second monomer could be replaced by any alkyl acrylate, only molecular weight determination would be hampered in such case.

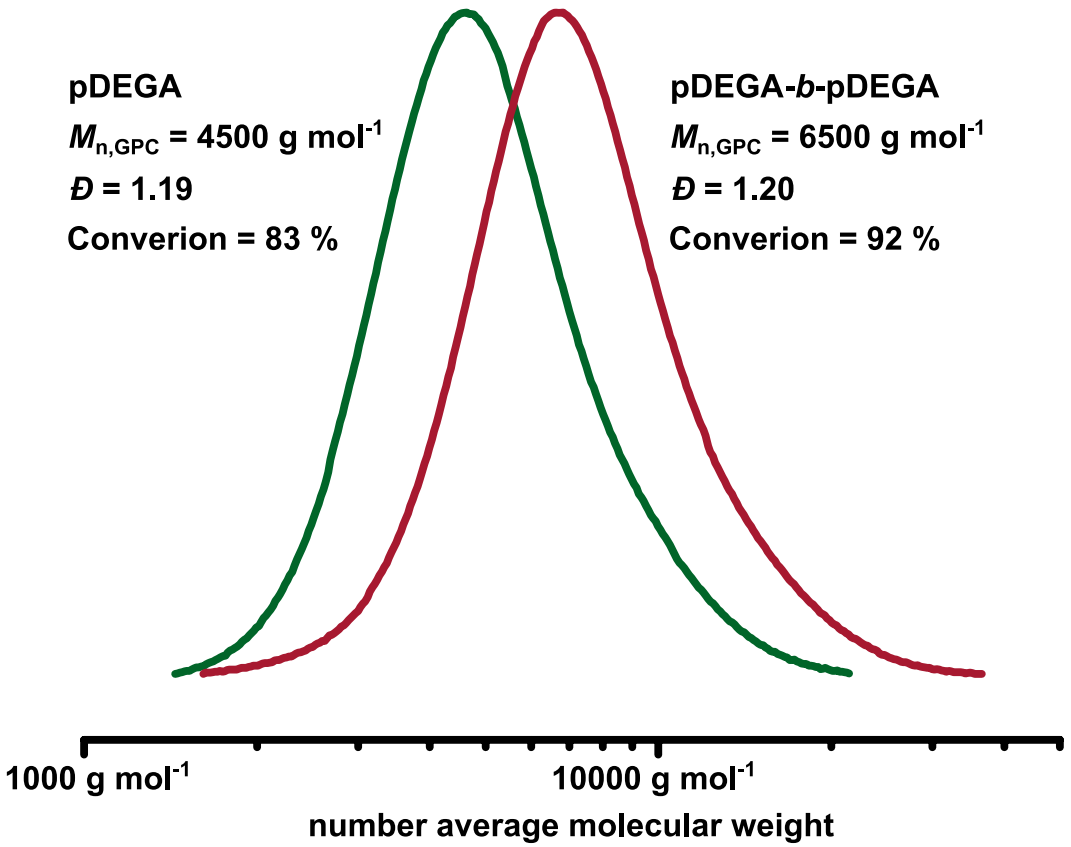


Figure 6 Molecular weight distributions of polymer obtained after the first and after the second reactor stage (both residence times set to 10 min per reactor coil).

Two examples of successful one step chain extension reactions in batch reactors via photoCMP are reported.[33] In both approaches, DMSO was employed. In here, we adopted the above tested H_2O/EtOH system to demonstrate the working principle of the coupled reactor setup, to not only accelerate block copolymer synthesis, but also to provide greener processing conditions at the same time. The reactor residence times were in both reactor stages set to 10 minutes, which allowed for a monomer conversion of 83 % and a number average molecular weight of 4500 g mol^{-1} ($Đ$ = 1.19, theoretical molecular weight of 4100 g·mol^{-1}, see Figure 6) in the first stage. The reactor outlet was then directly mixed with a DEGA/H_2O/EtOH solution (50/25/25 vol%) and injected in the second reactor. After further 10 minutes reaction time a polymer with a total molecular weight

of 6500 g mol^{-1} (theoretical molecular weight of 6100 g·mol^{-1}) and a dispersity of 1.2 was collected (Figure 6).

Conclusions

The synthetic scope of photo-induced copper mediated polymerization in continuous flow reactors has been expanded. A large variety of acrylate monomers can be successfully polymerized in tubular reactors in short reaction times to significant monomer conversions. The quality of the polymer products is throughout the series of monomers high, as indicated by the good agreement between calculated and experimentally obtained molecular weight and low dispersity of the products. Further, the regularly used solvent DMSO can be exchanged for an ethanol/water mixture when polar monomers are used, making the process inherently greener. A first scale-up of the polymerizations is successful, hinting also at the commercial viability of the photopolymerization, with over 200 g of high-definition polymer materials being available without large efforts in a relatively small sized photoreactor (16 mL internal volume). In a last step, also reactor couplings were determined, which allows in principle to obtain block copolymers in a single step procedure without requirement of intermediate polymer isolation.

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