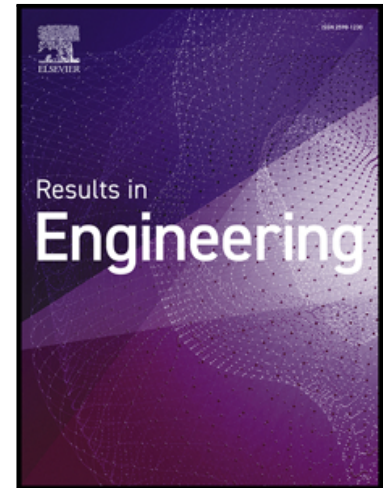


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Process-Chain Optimisation of SLA-Printed High-Temperature Resin for Short-Term Methanol Compatibility in Distillation Prototypes

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Abstract

Reliable prototyping of distillation internals requires rapid fabrication of complex geometries before committing to costly glass or metal equipment. Stereolithography (SLA) is well suited to this task, but the performance of printed photopolymers in hot methanol-containing environments depends strongly on the complete printing and post-processing route. This study investigates Formlabs High Temperature (HT) resin using gravimetric methanol uptake to establish a practical process chain for short-term distillation prototypes. This work provides a foundation for future studies on complex distillation column designs and their impact on separation performance, distillate purity, and the mechanical behavior of solvent-swollen materials. Per-layer exposure time (8–12 s), layer thickness (0.025–0.10 mm), UV post-cure temperature and duration (60–80 °C, 1–5 h), thermal post-curing (150–160 °C, 1–4 h), and support-removal timing were varied systematically. Longer exposure times during printing and higher UV post-cure temperatures reduced methanol uptake most effectively, while layer thickness showed a smaller secondary influence associated with interlayer cure quality. Thermal post-curing supported the removal of volatile species. Removing supports before UV curing improved chemical resistance by avoiding damage at attachment points. A fully post-processed SLA distillation column, cured at 80 °C for 2 h and thermally treated at 160 °C for 3 h, operated for 72 h (short-term) under continuous methanol–water reflux at 120 °C without visible structural failure, with a mass gain of 5.72 wt%. These results demonstrate that solvent resistance is governed not by resin selection alone, but by the integrated manufacturing process chain.

Keywords: Stereolithography; Additive manufacturing; Distillation; Methanol resistance; Post-processing

1. Introduction

Stereolithography (SLA), classified as a vat photopolymerization (VPP) process under ISO/ASTM 52900 [1], is widely used for rapid prototyping because it enables the fabrication of parts with high dimensional accuracy, fine feature resolution, smooth surfaces, and complex internal geometries [2]. These capabilities are particularly valuable in chemical engineering for laboratory-scale components such as reactors, distributors, and distillation internals, where thin walls and intricate structures may be difficult to machine or

mould and several design iterations are often required before a workable geometry is reached. In distillation, where trays and packings provide the surface area and contact time required for repeated vapour–liquid mass transfer [3, 4], SLA offers a practical route for testing new internal geometries directly from digital designs. Although conventional laboratory columns are typically fabricated from glass or metal because of their chemical and thermal stability, manufacturing or modifying these materials during early-stage development is often slow and costly. Additive manufacturing can therefore

accelerate geometric validation before designs are transferred to more durable materials or larger-scale fabrication.

The use of 3D printing in distillation has already been explored in several studies. Mardani et al. developed a modular polymer distillation column using FDM-printed ABS and reported methanol uptake of 0.5–1.5 wt% after 48 h [5]. Neukäuffer et al. built a laboratory-scale test rig using SLS-printed polyamide-12 (PA12) column internals – chosen over metal for cost reasons, and for its chemical resistance – and reported HETP values of roughly 0.20–0.35 m across gas loads of $F = 0.15\text{--}1.0\text{ Pa}^{0.5}$ for column diameters between 20 and 50 mm [6]. Their printed packing required a minimum crosspiece thickness of 0.8 mm, an order of magnitude thicker than the ~0.1 mm sheet metal of the conventional design, showing how AM constraints can already dictate part geometry before any solvent exposure is considered. In later work, the same group showed that iterative changes to printed packing geometry can improve separation performance [7]. Riese et al. demonstrated that metal additively manufactured structured packing can match conventional hydraulic performance while enabling geometries that are difficult to produce by standard routes [8]. Adapting a Raschig Super-Pak packing for laser melting required increasing the metal sheet thickness from 100 μm to 700 μm , which reduced porosity from 97% to 67% and the specific dry pressure drop roughly doubled relative to the conventional packing, despite a 14% larger specific surface area. Kotz et al. also highlighted the potential of SLA for high-resolution chemical-process components, while noting that standard acrylate resins can fail under demanding process conditions [9]. Overall, the existing literature shows the value of AM for distillation and chemical-process hardware, but most studies focus on geometry, hydraulics, or separation performance. However, the hot-solvent compatibility of SLA-printed polymers remains less established than their geometrical and hydraulic performance.

For SLA-printed distillation components, the final material performance is not determined by the resin formulation alone. Commercial SLA resins are commonly based on multifunctional acrylate or methacrylate monomers and oligomers, which form crosslinked networks during photopolymerisation [10, 11]. The final network depends on the exposure conditions during printing, layer thickness, washing, UV post-curing, thermal treatment, and practical handling steps such as support removal. During photopolymerisation, the reaction becomes increasingly

mobility-limited as the resin changes from a liquid to a rubbery and then glassy network [12, 13]. Complete conversion of all reactive groups is therefore not normally achieved in highly crosslinked SLA parts [2, 14]. Residual monomers, oligomers, additives, and photoinitiator-derived fragments may remain within the printed network.

When these parts are exposed to methanol-containing systems, two issues become important. The first is solvent uptake, which can cause swelling, dimensional change, and loss of functional reliability. This effect becomes more pronounced at elevated temperature because solvent transport and polymer-chain mobility both increase [15]. The second is the possible release of residual low-molecular-weight species into the contacting liquid, particularly photoinitiators such as Darocur 1173, which can be released into polar solvents with approximately 90% extraction within 8 days [16], which is relevant for process purity in solvent-contacting applications. Because both solvent uptake and leaching are diffusion-controlled transport processes, increased solvent ingress can facilitate the extraction of residual low-molecular-weight species from the polymer network [17]. In this study, leaching is recognised as an important concern, but it is not analytically quantified. Instead, gravimetric solvent uptake is used as the main indicator of methanol resistance, while targeted leachate identification and mechanical characterization are deferred to future work. Since solvent uptake generally correlates with leaching of residual species as well [16], the associated plasticization can compromise mechanical integrity [11] and thermomechanical properties at elevated operating temperatures [18].

Post-processing provides one of the most practical ways to improve the performance of SLA-printed parts. UV post-curing increases the conversion of remaining reactive groups and can improve crosslink density, dimensional stability, and chemical resistance [19, 20]. Thermal post-curing can further stabilise the network by promoting additional reaction of accessible residual groups, relieving internal stress, and removing volatile low-molecular-weight species [21, 22]. At the same time, excessive curing can lead to brittleness, discolouration, or other unwanted changes [11]. The useful processing window therefore has to be identified experimentally rather than assumed from default printer or resin settings.

For SLA components intended for chemical-process applications, these interconnected variables define a manufacturing design space within which printability, processing time, dimensional quality, and chemical

resistance must be balanced. This design space extends from parameters applied during layer formation, such as exposure time and layer thickness, to downstream operations including washing, support removal, UV post-curing, and thermal treatment. A condition that produces a geometrically successful print may therefore not necessarily produce a component with sufficient resistance to hot solvents. Exploring this design space is essential for identifying combinations of parameters that enable SLA parts to progress from visual or geometric prototypes to process components.

Printing parameters are equally important. Layer thickness and per-layer exposure time control cure depth, interlayer bonding, and build time. Insufficient exposure can leave weak or under-cured regions, whereas excessive exposure can reduce dimensional accuracy or increase brittleness [23, 24]. Washing before post-curing removes uncured surface resin, usually using isopropyl alcohol (IPA), but this step becomes more difficult for complex internal geometries where liquid resin can remain trapped [5]. Support handling is another practical variable that is often treated as routine, although it can affect the surface condition of thin or brittle parts after curing.

Although these individual steps are known to influence SLA part quality, their relative importance for solvent resistance has not been systematically compared for SLA-printed distillation components. Most published work either uses manufacturer-recommended settings or studies mechanical properties rather than hot-solvent performance. Methanol is a demanding test solvent for acrylate networks because of its polarity, small molecular size, and relevance to methanol-water distillation. A parameter study under methanol exposure therefore helps identify which parts of the SLA manufacturing route most strongly control the performance of printed distillation prototypes.

This work explores the manufacturing design space of SLA-printed Formlabs High Temperature resin for short-term methanol-water distillation prototypes. The investigated dimensions include per-layer exposure time, layer thickness, wall thickness, washing protocol, UV post-cure temperature and duration, thermal post-cure conditions, and support-removal timing. Methanol uptake is measured gravimetrically over exposure times ranging from several hours to 28 days and is used to compare the effect of each processing parameter. The optimised process chain is then applied to a printed distillation column operated under continuous methanol-water reflux conditions.

The aim is not to present SLA photopolymers as permanent replacements for glass or metal distillation

equipment. Rather, the goal is to show how the SLA process chain can be tuned so that printed acrylate components become suitable for prototyping under realistic methanol-water distillation conditions. By linking printing parameters, post-processing choices, solvent uptake, and column-level testing, this study provides practical guidance for using SLA beyond geometric prototyping and toward screening of chemically exposed process equipment.

2. Materials and Methods

2.1. Materials and Equipment

All specimens and distillation columns were printed using an Original Prusa SL1S Speed system, a masked stereolithography (MSLA) printer operating with a 405 nm UV LED array [25]. The Prusa SL1S Speed was selected because its open-material platform allows direct user control over per-layer exposure time and layer thickness, which was required to conduct the systematic printing-parameter study. The printer has an XY pixel size of 49 μm and was operated with layer thicknesses between 0.025 and 0.100 mm. Before the parameter study, the build platform was cleaned and recalibrated to ensure reliable first-layer adhesion and consistent layer thickness. The resin vat was inspected regularly, and the resin was gently mixed before printing to minimise settling without introducing air bubbles.

Formlabs High Temperature Resin was used as the printing material [26]. According to the manufacturer, the current version for this resin is V2 as of July 2026. This resin was selected because of its high thermal stability and suitability for high-resolution SLA printing. According to the manufacturer, it achieves a heat-deflection temperature of up to 238 °C after post-curing, which exceeds the operating temperature range considered for methanol-water distillation. The resin was stored in opaque containers at room temperature and gently shaken before filling the vat. The present study focuses on HT resin.

Post-processing was carried out using a Prusa CW1S washing unit, a Formlabs UV curing chamber, and a Heratherm convection oven. Methanol exposure tests were performed using sealed glass vessels placed on IKA ETS-D5 heating plates with external temperature probes. Methanol ($\geq 99.8\%$) and methanol-water (50:50 mol%) mixtures were used as test liquids. The experiments were performed in a standard laboratory environment without active enclosure temperature control; room-temperature variations were monitored but not treated as an experimental variable.

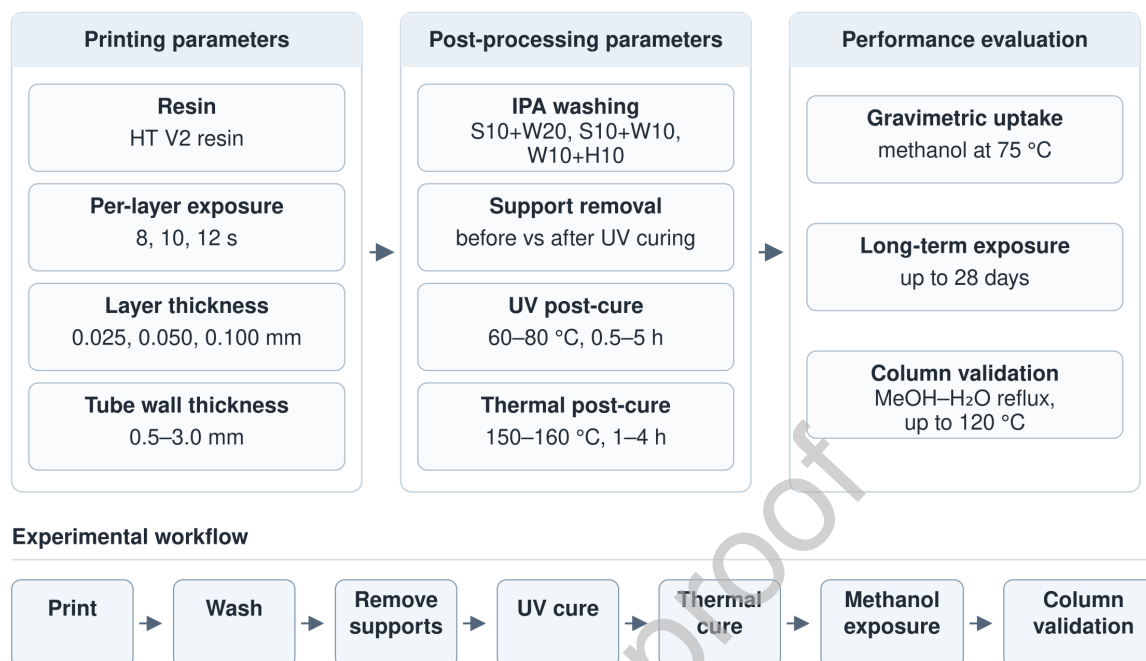


Figure 1: Overview of the SLA process chain and experimental parameters investigated in this study

2.2. Specimen Design and Printing

Test geometries were designed in Autodesk Fusion software and exported as STL files. The files were imported into PrusaSlicer 2.9.2, where the layer thickness, exposure time, and build-plate arrangement were defined before export to the printer. Hollow tube specimens were used as the main test geometry because they represent the thin-walled features relevant to printed distillation components. The tubes had an outer diameter of 12 mm and a height of 15 mm, with wall thicknesses between 0.5 and 3.0 mm, depending on the experiment. Rectangular sheet specimens were also printed for selected comparison tests where a simpler geometry was useful for evaluating uptake behaviour.

The main printing variables were per-layer exposure time and layer thickness. Normal-layer exposure times of 8, 10, and 12 s were tested. The base layers were exposed for 28–32 s to ensure adhesion to the build platform during printing. Three layer thicknesses were investigated: 0.025, 0.050, and 0.100 mm. All specimens used for methanol exposure were printed in the same orientation so that build orientation was not introduced as an additional variable. Unless support-removal timing was being studied directly, supports were removed after washing and before UV

post-curing. The build platform was cleaned with IPA and recalibrated between print jobs.

2.3. Post-Processing Protocols

Freshly printed specimens were washed in isopropyl alcohol (IPA, ≥99.8%) using the Prusa CW1S washing unit, the standard rotary dip-wash cycle to remove uncured surface resin. Three washing protocols were compared: 10 min soaking followed by 20 min washing (S10+W20), 10 min soaking followed by 10 min washing (S10+W10), and 10 min washing followed by 10 min thermal drying (W10+H10). For column prototypes and other parts with internal channels, IPA was manually flushed through the structure to improve removal of trapped resin. After washing, all parts were air-dried until no visible solvent remained before UV curing.

UV post-curing was performed in a Formlabs curing chamber at controlled temperature. The main UV curing temperatures were 60 and 80 °C, and curing times ranged from 0.5 to 5 h depending on the parameter set. Thermal post-curing was then carried out in a Hera therm convection oven at 150 or 160 °C for 1–4 h in ambient air. The temperature was allowed to stabilise before placing the specimens in the oven.

Several post-processing combinations were used to separate the influence of UV curing, thermal curing, and cure sequence. Table 1 gives a representative set of the protocols used for 2.5 mm wall-thickness tube specimens.

Support-removal timing was treated as a separate practical variable. In the standard procedure, supports were removed after washing but before UV curing. For comparison, selected specimens were cured with supports still attached and the supports were removed only after post-curing.

The complete experimental workflow, from printing to column-level compatibility, is illustrated in Fig. 1.

2.4. Methanol Exposure and Gravimetric Uptake Measurements

Gravimetric methanol uptake was used as the main quantitative indicator. Although the measured mass change may also be influenced by leaching of residual species, *methanol uptake* is expected to represent the dominant contribution under the investigated conditions in this work. Pure methanol was used for accelerated solvent exposure, while a 50:50 mol% methanol-water mixture was used to represent the liquid environment relevant to methanol-water distillation. Most specimen-level accelerated tests were carried out in methanol at 75 °C. Selected tests and column-level compatibility tests were performed under methanol-water distillation conditions at temperatures up to 120 °C.

For immersion tests, specimens were placed in sealed glass vessels containing the test liquid and heated with external temperature probes. Specimens were removed at defined time intervals, typically 15 min, 30 min, 1 h, 2 h, 3 h, 4 h, and longer exposure times depending on the test duration. Some experiments included heating periods followed by room-temperature soaking to represent start-up and shut-down conditions during distillation operation. Long-term measurements were continued for up to 28 days.

Mass gain was measured using an analytical balance with a readability of 0.0001 g. The measurement procedure followed the principles of ISO 175, ISO 62, and ASTM D570, with modifications for methanol exposure at elevated temperature [27–29]. Each specimen was dried before testing, and the initial dry mass was recorded as M_0 . At each measurement time, the specimen was removed from the liquid using tweezers, gently blotted with lint-free tissue without rubbing, and weighed within 60 s to minimise evaporative losses. The method was applied consistently across all specimens

and conditions, ensuring that relative rankings and comparative conclusions remain valid. The mass change was calculated as

$$\Delta m (\%) = \frac{M_t - M_0}{M_0} \times 100, \quad (1)$$

where M_t is the specimen mass at exposure time t . For each parameter set, replicate specimens were measured individually, typically in triplicate unless otherwise stated, and results were reported as mean values with standard deviations. For specimens where equilibrium was reached, it was defined as the point at which the change between two successive measurements was less than 0.1% over 24 h.

2.5. Distillation Compatibility Experiment

The distillation column contained gyroid-type internal features designed to increase vapour-liquid contact area and was printed as a single SLA component after the specimen-level process parameters had been selected.



Figure 2: SLA-printed HT resin column prototypes with gyroid-type internal features used for methanol-water distillation experiment.

For column-level compatibility test, the selected process route consisted of UV post-curing at 80 °C for 2 h followed by thermal post-curing at 160 °C for 3 h. After printing, the column was washed and processed using this route before assembly in the distillation setup. The column mass was recorded after post-curing, after attachment of the flexible tubing, and again after the distillation experiment following removal of the tubing. This sequence allowed the mass change of the printed column itself to be separated from the attached tubing and insulation.

Table 1: Representative post-processing protocols used for 2.5 mm wall-thickness tube specimens.

Protocol	Notation	UV Cure	Thermal Cure
1	UV2+T3	80 °C, 2 h	160 °C, 3 h
2	UV1+T3	80 °C, 1 h	160 °C, 3 h
3	UV5	80 °C, 5 h	None
4	UV2+T3+UV1	80 °C, 2 h + 1 h later	160 °C, 3 h

The column was operated under continuous methanol-water reflux conditions at temperatures up to 120 °C. After the experiment, the column was inspected visually for deformation, cracking, or other signs of structural failure, and the final mass gain was calculated using Eq. 1.

3. Results and Discussion

3.1. Effect of Printing Parameters on Methanol Uptake

The printing parameters define the initial quality of the cured network and therefore influence the chemical resistance of SLA-printed parts exposed to methanol. Three per-layer exposure times, 8, 10, and 12 s, were evaluated using 2.5 mm wall-thickness tube specimens printed with a 28 s base-layer exposure. All specimens were post-processed using the selected route of UV curing at 80 °C for 2 h followed by thermal curing at 160 °C for 3 h.

Methanol uptake decreased consistently as the per-layer exposure time increased, as shown in Fig. 3. After 6 h in methanol, specimens printed at 8 s reached 2.267 wt%, whereas specimens printed at 12 s reached 1.960 wt%. This corresponds to a reduction of 0.307 wt%. The improvement from 10 to 12 s was slightly larger than the improvement from 8 to 10 s, indicating more pronounced returns at the highest exposure used in this study.

From a processing perspective, increasing the exposure time from 8 to 10 s improved methanol resistance, while a further increase to 12 s provided an additional reduction in methanol uptake. Although the improvement from 10 to 12 s came at the cost of a longer print time, 12 s provided the lowest uptake among the conditions investigated and is therefore the preferred exposure time when methanol resistance is the primary design criterion. The lower uptake at higher exposure can be attributed to improved layer curing, stronger interlayer bonding, and a lower amount of residual reactive material within the printed part. This trend agrees with the general role of exposure dose in vat photopolymerisation, where insufficient exposure

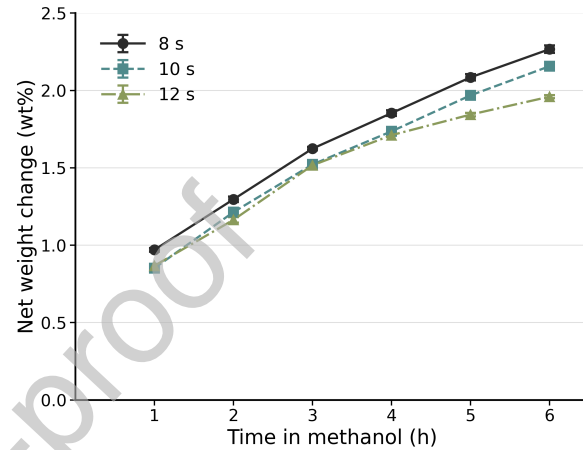


Figure 3: Effect of per-layer exposure time on methanol uptake of 2.5 mm wall-thickness HT resin tube specimens. Error bars indicate standard deviation, $n = 4$.

can produce weaker layer interfaces and less complete curing [23, 24].

Layer thickness also affected long-term methanol uptake, although its influence was smaller than that of exposure time and post-processing. Tube specimens printed at layer thicknesses of 0.025, 0.050, and 0.100 mm were exposed to methanol for 28 days at room temperature. The 0.100 mm specimens reached 4.46 wt% after 28 days, compared with 4.01 wt% for the 0.025 mm specimens, as shown in Fig. 4. The difference of approximately 0.45 wt % suggests that thicker printed layers may introduce more pronounced interlayer regions where local bonding is less complete. The 0.050 mm layer thickness therefore provides a practical compromise between build time, print quality, and methanol resistance.

Wall thickness influenced the time-dependent uptake behaviour. Thinner walls gained mass more rapidly and reached high uptake values earlier than thicker walls. For example, 0.5 mm wall specimens showed a rapid initial mass increase during the first hours of exposure, whereas 1.5 and 2.0 mm wall specimens gained mass more gradually over the same period. This can be observed in Fig. 5.

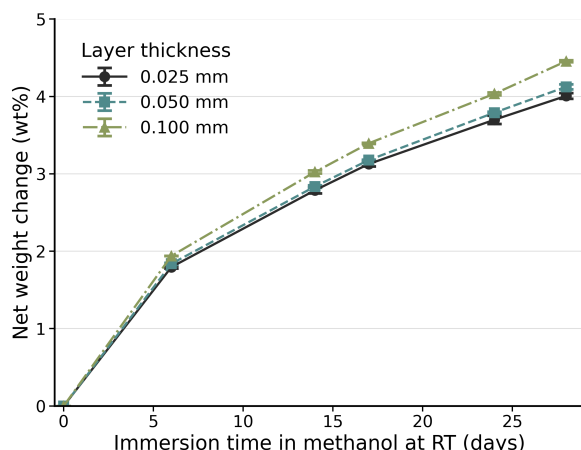


Figure 4: Effect of layer thickness on long-term methanol uptake of 2.5 mm wall-thickness HT resin tube specimens immersed in methanol at room temperature ($\sim 22^\circ\text{C}$). Error bars indicate standard deviation, $n = 3$.

This does not mean that thicker walls prevent methanol uptake. Instead, thicker walls delay the uptake process and extend the useful operating window before large dimensional changes occur. For printed distillation components, this is an important design point: thin internal features may be acceptable for short-term tests.

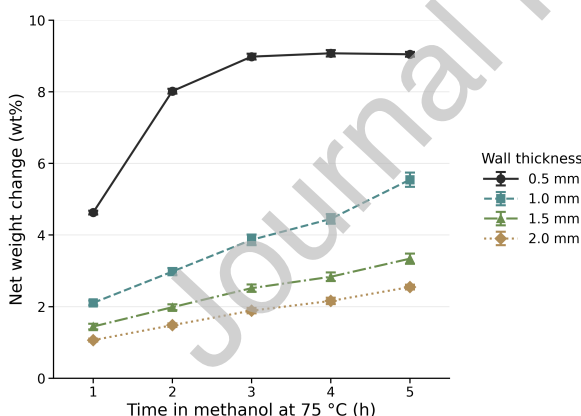


Figure 5: Effect of wall thickness on methanol uptake at $\sim 75^\circ\text{C}$. Error bars indicate standard deviation, $n = 3$.

Overall, the printing parameters are not only dimensional or productivity variables. They directly affect the final material quality and therefore the methanol resistance of the printed component. Post-processing can substantially improve the material response, but it cannot fully compensate for an under-exposed or poorly bonded print.

From a component-design perspective, wall thickness should be treated as a functional variable rather than only as a geometric constraint. Thin walls and fine internal features enable compact and complex column geometries but undergo more rapid solvent uptake. They may therefore be suitable for short-term internal features, whereas load-bearing walls, sealing regions, and external boundaries should be designed with sufficient thickness to delay swelling and preserve dimensional stability.

3.2. Effect of Post-Processing on Methanol Uptake

3.2.1. Washing Protocol

The washing step was evaluated using three IPA-based protocols: 10 min soaking followed by 20 min washing (S10+W20), 10 min soaking followed by 10 min washing (S10+W10), and 10 min washing followed by 10 min thermal drying (W10+H10). For the HT resin tube specimens, the differences between the washing protocols were small. At 5 h in methanol at 75°C , S10+W20 gave approximately 2.35 wt% uptake, while S10+W10 gave approximately 2.31 wt%. The difference of about 0.04 wt% is within the practical uncertainty of the gravimetric method and is much smaller than the effects observed for UV curing, thermal curing, or support handling.

This result indicates that, once the surface resin is adequately removed, extending the IPA washing time does not strongly improve methanol resistance for the tube specimens studied here. Washing remains essential, particularly for parts containing internal channels or complex geometries, because uncured resin can remain trapped in enclosed regions. For this reason, the column prototypes were flushed manually with IPA in addition to standard washing. For HT resin parts of the type studied here, a minimum of 10 min fresh IPA contact was sufficient before drying and post-curing.

3.2.2. UV Post-Curing Temperature and Duration

UV post-curing had a strong effect on methanol uptake. Increasing the UV post-cure temperature from 60 to 80°C reduced uptake more effectively than simply increasing the cure duration from 60 to 120 min at 60°C . At 10 s printing exposure and 120 min UV curing, the 80°C condition gave lower uptake than the 60°C condition at both short and longer exposure times. This effect was observed for both tube and sheet specimens, showing that the improvement was not limited to a single sample geometry. As shown in Fig. 6, methanol uptake increased with immersion time for all UV post-cure conditions, confirming progressive

methanol diffusion into the polymer network. However, the specimens cured at 80 °C for 120 min showed the lowest uptake throughout the test. In contrast, the two 60 °C conditions remained close to each other, indicating that extending the curing time from 60 to 120 min at 60 °C provided only a limited improvement. This suggests that UV post-cure temperature was more effective than UV post-cure duration within the range investigated.

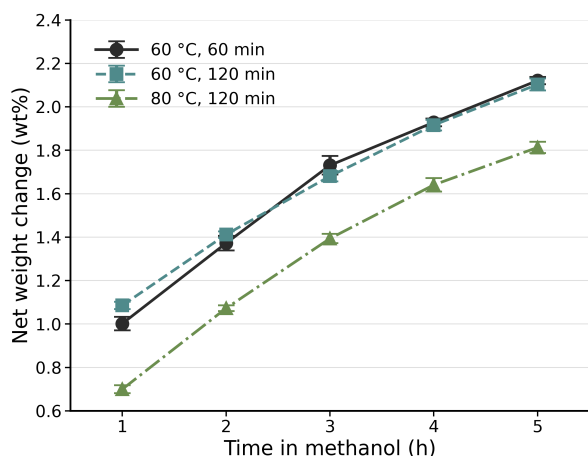


Figure 6: Effect of UV post-cure temperature and duration on methanol uptake of SLA-printed HT resin specimens immersed in methanol. Error bars indicate standard deviation, $n = 3$.

The improved performance at 80 °C can be explained by the temperature dependence of post-curing. As the photopolymer network forms, the remaining reactive groups become increasingly restricted by reduced molecular mobility. At a higher post-cure temperature, the network has greater mobility, allowing additional curing to occur more effectively than at a lower temperature [12, 13]. Extending the curing time at too low a temperature therefore provides only limited benefit. Similar effects have been reported for photopolymer networks, where conversion and final properties depend strongly on the balance between light exposure, temperature, and network mobility [19, 20].

The comparison between 8 and 10 s printing exposure under the same UV post-cure condition also showed that post-curing cannot fully correct a low print exposure. Reducing the per-layer exposure from 10 to 8 s increased methanol uptake even after UV curing at 80 °C for 120 min. This confirms that the network formed during printing remains important for the final solvent resistance.

The best UV-only condition in this study was 80 °C for at least 2 h. Longer UV curing gave only limited

additional improvement once this condition had been reached. Therefore, UV curing at 80 °C for 2–3 h was selected as the practical post-cure window for HT resin distillation prototypes.

3.2.3. Thermal Post-Curing

Thermal post-curing was introduced after UV curing to improve material stability and remove residual volatile species. The selected thermal treatment was 160 °C for 3 h. This temperature is below the manufacturer-reported heat-deflection temperature of fully post-cured HT resin, but high enough to promote additional network stabilisation.

The effect of thermal curing on the final measured methanol uptake was smaller than the effect of UV curing. When the UV cure was already sufficient, especially after 2 h at 80 °C, the additional reduction in uptake after thermal curing was limited. Under shorter UV curing conditions, thermal treatment had a larger effect because more residual reactive material remained available.

A consistent mass loss of approximately 0.44–0.47 wt% was observed during thermal treatment across the tested conditions. This mass loss is attributed mainly to the removal of residual volatile or low-molecular-weight species rather than to structural degradation. Although thermal curing did not always produce the lowest short-term uptake, it improved the consistency of the process and is expected to be beneficial for long-term dimensional and chemical stability. Thermal post-curing was therefore retained in the recommended process chain.

3.2.4. UV Cure Duration and Process-Route Comparison

Several post-processing combinations were compared to separate the effects of UV duration, thermal curing, and process sequence. For 2.5 mm wall-thickness tube specimens printed at 12 s exposure and 0.050 mm layer thickness, the route UV 80 °C/2 h followed by thermal curing at 160 °C/3 h gave the lowest and most consistent long-term uptake. After 28 days, this route reached 5.16 wt%. UV curing for 5 h without thermal treatment reached 5.47 wt%, only 0.31 wt% higher, showing that extended UV curing alone can approach the performance of the combined route. To accelerate ageing, samples were initially exposed to methanol at ~75 °C for 10 h, then left at RT for the remaining time.

As shown in Fig. 7, the selected UV2+T3 route produced the lowest 28-day methanol uptake among the compared post-processing routes. UV curing for

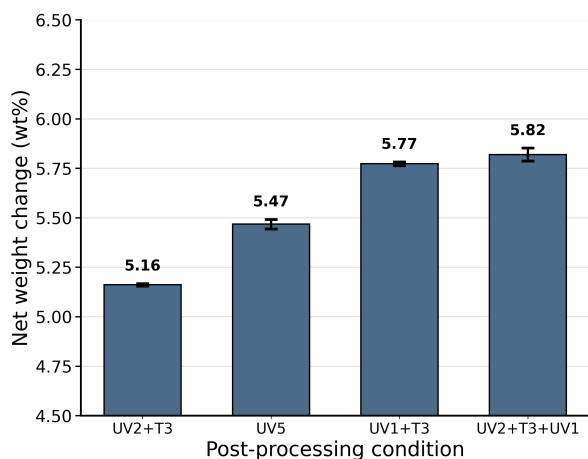


Figure 7: Methanol uptake after 28 days for selected post-processing routes. UV2+T3 denotes UV curing at 80 °C for 2 h followed by thermal curing at 160 °C for 3 h. The y-axis is zoomed to highlight endpoint differences between routes. Error bars indicate standard deviation, $n = 3$.

5 h without thermal treatment gave a slightly higher uptake, indicating that extended UV curing alone can approach but did not surpass the combined UV and thermal route. The UV1+T3 route resulted in higher uptake, confirming that 1 h of UV curing before thermal treatment was insufficient. Adding an additional UV step after UV2+T3 also did not improve performance. However, the combined UV and thermal route remains preferable because it also removes volatile species and provides a more stable post-processing sequence. Adding an extra UV step after thermal curing did not improve the result. The additional UV step produced a slightly higher 28-day uptake than the standard UV2+T3 route. For this study, the practical conclusion is that additional UV curing after the selected UV and thermal treatment did not provide a measurable benefit. Once a high degree of conversion has been achieved, further UV exposure is unlikely to substantially improve the network structure and may instead promote a stiffer, more brittle material due to the highly crosslinked polymer network [30].

The comparison between 1 h and 2 h UV curing at 80 °C was especially important. With the same thermal treatment, the 2 h UV-cured specimens reached lower long-term uptake than the 1 h UV-cured specimens. This confirms that 1 h at 80 °C is not sufficient for the HT resin specimens studied here, while 2 h provides a practical minimum. A 2–3 h UV cure at 80 °C is therefore recommended before thermal post-curing.

3.2.5. Importance of UV Post-Curing Before Methanol Exposure

The difference between fully post-cured specimens and IPA-washed green parts was large. Fully post-cured tubes showed a predictable dependence on wall thickness: thinner walls gained mass more rapidly, while thicker walls showed a slower mass increase. In contrast, green parts showed much higher and less stable mass changes during methanol exposure.

For thin green specimens, the mass increased rapidly during the first hour and then decreased over the following hours. This behaviour reflects two competing processes: methanol entering the polymer network and uncured or low-molecular-weight resin components leaving the part. Thicker green specimens retained more uncured material and continued to show high mass changes over the test period. Because of this mixed behaviour, green-part uptake cannot be interpreted as a reliable material property.

This comparison confirms that UV post-curing is essential before any meaningful solvent-resistance test. It is also essential for column operation. Without sufficient post-curing, the printed part is not a stable crosslinked component but a partially cured structure that can both absorb methanol and release material into the liquid.

3.2.6. Support-Removal Timing

Support-removal timing had a measurable effect on methanol uptake. Specimens cured with supports still attached and removed only after post-curing showed higher uptake than specimens whose supports were removed after washing and before UV curing. The effect was thickness-dependent. At 5 h, the largest difference occurred for 1.0 mm wall specimens, where delayed support removal increased uptake by approximately 1.94 wt%. The effect was smaller for 1.5 and 2.0 mm walls, and negligible for 0.5 mm walls, where the specimens reached high uptake rapidly regardless of support condition.

As shown in Fig. 8, the influence of support-removal timing was most pronounced for the 1.0 mm wall-thickness specimens. Removing supports after UV curing increased the methanol uptake compared with removing supports before UV curing. A similar trend was also observed for the 1.5 and 2.0 mm specimens, although the magnitude of the difference was smaller. For the 0.5 mm specimens, both conditions showed high uptake, suggesting that very thin walls become rapidly saturated and the effect of support-removal timing is less distinguishable.

The most likely explanation is local surface damage

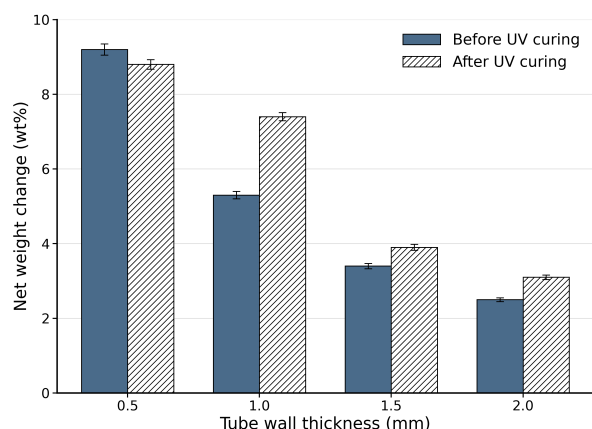


Figure 8: Effect of support-removal timing on methanol uptake after 5 h for SLA-printed HT resin tube specimens with different wall thicknesses. Error bars indicate standard deviation, $n = 3$.

at support contact points. Once the part has been fully cured, the resin is stiffer and more brittle, so removing supports can leave small cracks, fractured regions, or roughened surfaces. These defects provide easier entry points for methanol. For very thin specimens, the whole wall is affected rapidly, so the support effect is partly masked. For intermediate wall thicknesses, the defect contribution becomes more visible.

Based on these results, support removal after washing but before UV post-curing should be treated as part of the process chain, not as a minor handling detail. This step is especially important for thin-walled distillation components, where support marks may lie close to functional surfaces.

3.2.7. Post-Processing Summary

The recommended process chain for HT resin distillation prototypes is: IPA washing for at least 10 min, support removal before UV curing, UV post-curing at 80 °C for 2–3 h, and thermal post-curing at 160 °C for 3 h. Among the post-processing variables, UV curing and support-removal timing had the largest effects on methanol uptake. Thermal curing had a smaller direct effect on final uptake, but remained important for removing volatile species and improving process stability. Washing protocol had the smallest effect once sufficient IPA contact had been achieved.

The practical outcome of the printing and post-processing study is summarised in Table 2. The table ranks the process variables in the order in which they appear in the manufacturing route and links each recommended condition to its observed effect on methanol uptake.

Overall, the most important practical controls were sufficient UV post-curing and support removal before UV curing, while washing had only a minor influence once uncured surface resin had been removed.

3.3. Long-Term Net Mass Change under Two Exposure Conditions

Long-term exposure showed that methanol uptake continued beyond the first few hours, even after the rapid initial mass increase had slowed. In the 28-day tests, the specimens approached a slower uptake regime but did not always reach a clear final plateau, especially for thicker walls. This means that short tests are useful for ranking process parameters, but they should not be treated as full lifetime tests.

Some experiments included heating periods followed by room-temperature soaking and later reheating. Once the specimens had already gained mass during the initial methanol exposure, cooling and reheating caused only small additional changes in measured mass. This suggests that most of the rapid uptake occurs during the first exposure period. For practical distillation testing, this is encouraging because start-up and shut-down cycles did not trigger a new large mass increase after the first uptake period.

Pure methanol at 75 °C was compared with a 50:50 mol% methanol-water mixture at temperatures up to 120 °C, representing the more realistic distillation environment.

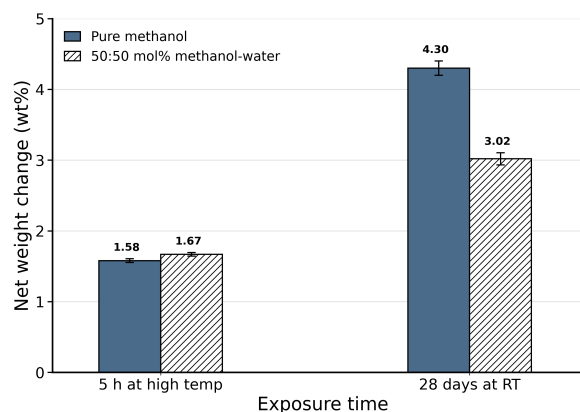


Figure 9: Comparison of solvent uptake in pure methanol at 75 °C and in a 50:50 mol% methanol-water mixture at 120 °C after 5 h and 28 days of exposure. Error bars indicate standard deviation, $n = 3$.

As shown in Fig. 9, the 50:50 mol% methanol-water condition produced slightly higher uptake after 5 h, while pure methanol produced substantially higher uptake after 28 days. Pure methanol reached approximately 42% higher uptake than

Table 2: Parameter hierarchy based on the observed influence on methanol uptake.

Rank	Parameter	Effect on $\Delta\text{wt}\%$	Primary mechanism
1	UV cure duration: 1 h vs 2 h	Up to 2.30 wt% reduction	Vitrification limit
2	Support removal: before vs after UV	Up to 1.94 wt% increase if after UV	Crack formation
3	Exposure time: 10 s vs 8 s	$\sim 0.3\text{--}0.5$ wt% reduction for 10 s	Greater degree of cure
4	Layer thickness: 0.025 vs 0.10 mm	0.45 wt% reduction for thinner layers	Interlayer cure homogeneity
5	UV cure temperature: 80 °C vs 60 °C	0.08–0.30 wt% reduction	Chain mobility during cure
6	Thermal cure addition	0.10–0.30 wt% reduction	Additional crosslinking and leachate removal
7	Wash protocol	<0.05 wt%, negligible	Surface cleanliness only

the methanol-water mixture after 28 days. This shows that the severity of the exposure condition was not determined by temperature alone, but also by solvent composition and exposure duration.

Methanol is a small, polar solvent and can interact strongly with acrylate-based networks, while the presence of water reduces the effective methanol content in the liquid mixture. The lower long-term uptake in the methanol-water mixture is therefore consistent with the general role of solvent-polymer affinity in swelling behaviour [15, 31]. Although the methanol-water mixture represents the realistic distillation environment, pure methanol at 75 °C can be treated as the more conservative long-term screening condition for methanol-water distillation prototypes.

3.4. Methanol-Water Total-Reflux Distillation

The selected process chain was applied to an SLA-printed HT resin distillation column with gyroid-type internal features. The column was UV post-cured at 80 °C for 2 h and thermally post-cured at 160 °C for 3 h before assembly in the distillation setup. Mass changes during post-processing were tracked before the distillation test. The UV cure caused a mass loss of approximately 0.575 wt%, and the thermal cure caused a further loss of approximately 0.46 wt%. These losses are consistent with the removal of residual solvent or volatile low-molecular-weight species during post-processing.

During methanol-water reflux at temperatures up to 120 °C, the printed column retained its shape and macroscopic integrity and allowed continued reflux operation. After 24 h of operation, the column gained 2.1 wt%. After 72 h under the same operating

conditions, the mass gain reached 5.72 wt%. No visible deformation, cracking, fracture, flooding or leaking was observed after the 72 h test. The reported mass gain includes both solvent uptake and leaching of residual species, so the comparative rankings of process parameters remain valid because leaching effects are minimal with respect to solvent uptake across all specimens.

This result is important because the column-level compatibility test combines the effects of geometry, post-processing, solvent exposure, and operating temperature in a single functional test. The uptake was not negligible, so HT resin should not be treated as a permanent replacement for glass or metal equipment. However, the absence of structural failure shows that, with the selected process chain, SLA-printed HT resin columns can be used for short-term functional prototyping under methanol-water reflux conditions.

3.5. Limitations of the Study

This study used gravimetric methanol uptake as the main performance indicator. Although this method is sensitive and directly relevant to swelling and dimensional stability, it does not quantify the retention of mechanical properties or thermomechanical properties or identify species released into the liquid phase. Our application of methanol-water distillation does not induce mechanical loads. Hence, mechanical characterization of methanol-saturated specimens was not performed. The 72 h column result should be interpreted strictly as short-term survival without visible failure.

The longest specimen-level exposure lasted 28 days in this work. Some specimens were still gaining

mass slowly at the end of this period, so the reported long-term values should be interpreted as extended uptake values rather than guaranteed final values. Longer tests would be needed to establish performance limits for thicker components.

The specimen geometries were simplified tubes and rectangular sheets. These geometries were useful because they isolated the effects of wall thickness, exposure time, and post-processing. Real distillation columns contain more complex internal structures, junctions, end regions, and support-contact areas. The column validation partly addressed this gap, but further testing with different column geometries would be needed before broader design rules can be established.

Finally, all major optimisation experiments were carried out using Formlabs HT resin. The trends observed here may be relevant to similar acrylate or methacrylate SLA resins, but the numerical values should not be transferred directly to other resin chemistries. Each resin system will require its own process window, especially when exposed to hot polar solvents.

4. Conclusion

This study developed and evaluated an SLA-based process chain for producing prototype components for methanol-water distillation. When printed and post-processed under the selected conditions, HT resin components showed sufficient short-term stability for laboratory validation. During the 72 h continuous distillation trial at temperatures up to 120 °C, the printed column gained 5.72 wt% but showed no visible cracking, deformation, or loss of function. Although solvent uptake was not eliminated, it was delayed enough to allow short-term prototype testing.

The results showed that methanol resistance depends primarily on the quality of the cured polymer network. Increasing the per-layer exposure time reduced methanol uptake, while UV post-curing at 80 °C was more effective than curing at 60 °C. A UV cure duration of 2–3 h provided the most practical balance between solvent resistance and processing time. Thermal post-curing at 160 °C for 3 h gave a smaller direct reduction in uptake, but remained useful for removing residual volatile species and stabilising the network.

Support-removal timing also influenced the final solvent response. Removing supports after UV curing increased methanol uptake, most likely due to local surface damage at support-contact points. Therefore, support removal after washing and before

UV post-curing is recommended for methanol-exposed SLA components.

Overall, the recommended process chain consists of IPA washing, support removal before UV curing, UV post-curing at 80 °C for 2–3 h, and thermal post-curing at 160 °C for 3 h. This route enabled 72 h of functional methanol–water reflux operation without visible structural failure, while the measured solvent uptake limits HT resin to short-term prototype applications.

5. Abbreviations

AM	Additive Manufacturing
CAD	Computer-Aided Design
SLA	Stereolithography
MSLA	Masked Stereolithography
UV	Ultraviolet
VPP	Vat Photopolymerization
FDM	Fused Deposition Modelling
SLS	Selective Laser Sintering
STL	Standard Tessellation Language
HT	High Temperature
ABS	Acrylonitrile Butadiene Styrene
HETP	Height Equivalent to a Theoretical Plate
HDT	Heat Deflection Temperature
IPA	Isopropyl Alcohol
RT	Room Temperature

6. Symbols

M_t	Mass of specimen at time t
h	Layer thickness
M_0	Initial dry mass of specimen
n	Number of samples

Data availability

The experimental data supporting the findings of this study are available on request.

CRediT authorship contribution statement

Neha Kumari: Methodology, Investigation, Formal analysis, Visualization, Data curation, Writing – original draft. **Vignesh Jayavelu:** Conceptualization, Validation, Visualization, Writing – review and editing. **Christoph Klahn:** Supervision, Writing – review and editing.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT and Claude to support language editing and manuscript restructuring. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of interests

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