

# Real-Time Spectroscopic Analysis Enabling Quantitative and Safe Consumption of Fluoroform during Nucleophilic Trifluoromethylation in Flow

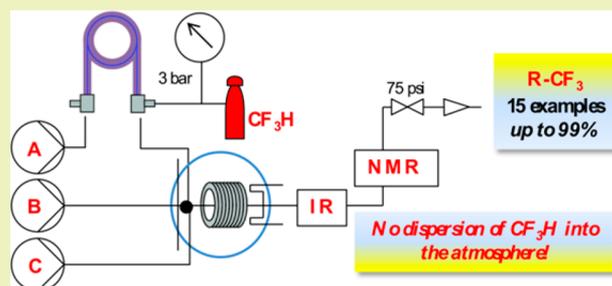
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## Supporting Information

**ABSTRACT:** The productive use of toxic waste materials derived from industrial processes is one of the main goals of modern chemical research to increase sustainability of the large-scale production. Here we devise a simple and robust strategy for the utilization of trifluoromethane, obtained in large quantities from polytetrafluoroethylene manufacture, and the conversion of this greenhouse gas into valuable fluorinated compounds. The generation of the trifluoromethyl carbanion and its direct and complete consumption through trapping with a number of electrophiles were achieved by a fully contained flow reactor setup. The adoption of modern in-line analytical tools, such as portable Fourier transform infrared and nuclear magnetic resonance devices, allowed the accurate reagent dosing with considerable benefits in terms of controlling the environmental impact during this continuous process. The advantages of the method, with respect to the batch procedure, will be discussed and demonstrated experimentally.

**KEYWORDS:** Trifluoromethylation, Continuous process, In-line analysis, Benchtop NMR, Fluoroform



## INTRODUCTION

There is a clear need to develop modern synthetic strategies which employ renewable starting materials. Furthermore, there is also a need to convert waste materials derived from certain industrial processes into valuable synthetic compounds improving the sustainability of large-scale production.<sup>1–3</sup> A case in point is the industrial manufacture of polytetrafluoroethylene (PTFE) which generates very large amounts of trifluoromethane ( $\text{CF}_3\text{H}$ ) as a byproduct.<sup>4</sup>  $\text{CF}_3\text{H}$  is listed as a potent greenhouse gas, with a lifetime of 270 years, which is the approximate amount of time it would take for  $\text{CF}_3\text{H}$  concentration to return to its natural level.<sup>5</sup> Its disposal requires expensive procedures, such as high-temperature incineration. Consequently, there is interest in the development of affordable transformations which utilize  $\text{CF}_3\text{H}$  for the direct generation of useful functional fluorinated compounds,<sup>6–12</sup> which are endowed with improved medicinal or physical-chemical properties.<sup>13–15</sup> In particular, significant advances have been achieved during the past decade in the development of new reagents and general approaches for trifluoromethylation, including electrophilic, radical, and nucleophilic reactions.<sup>16–24</sup> Among these methods, the use of  $\text{CF}_3\text{H}$  for installing directly the trifluoromethyl moiety into an organic compound remains an appealing approach, in terms of raw material availability and atom economy. Nevertheless, as a greenhouse gas,  $\text{CF}_3\text{H}$  must not be dispersed into the atmosphere. Thus, an accurate determination of  $\text{CF}_3\text{H}$  is vital during the usage of this reagent to make it ecosustainable and

chemically efficient. The recent introduction of flow technologies into modern laboratory practice has enabled the improved performance of gas–liquid reactions by expediting the mass transfer between the two phases.<sup>25–32</sup> In particular, membrane-based reactors have been successfully applied to enable the gas–liquid contact, avoiding the occurrence of biphasic flow regime, which may lead to less efficient and controllable dosing of the gas.<sup>33</sup> A few years ago we contributed to the development of a tube-in-tube reactor for gas–liquid reactions, consisting of a pair of concentric capillaries in which the central capillary functions as a gas-permeable membrane (Teflon AF-2400).<sup>34,35</sup> This system has been applied to several synthetic programs, exploiting the permeability of Teflon AF-2400 to a range of gases (carbon monoxide, hydrogen, ozone, carbon dioxide, oxygen, ammonia, ethylene, and diazomethane).<sup>36–42</sup> More importantly, the advent of a number of innovative in-line analytical tools has greatly advanced reaction monitoring and subsequent adjustment of reaction conditions.<sup>43–46</sup> In this context, an increasing number of new applications have been reported on the use of portable flow IR devices<sup>47–50</sup> and benchtop low-field NMR equipment,<sup>51–56</sup> which greatly enabled real-time monitoring of continuous flow chemistry.

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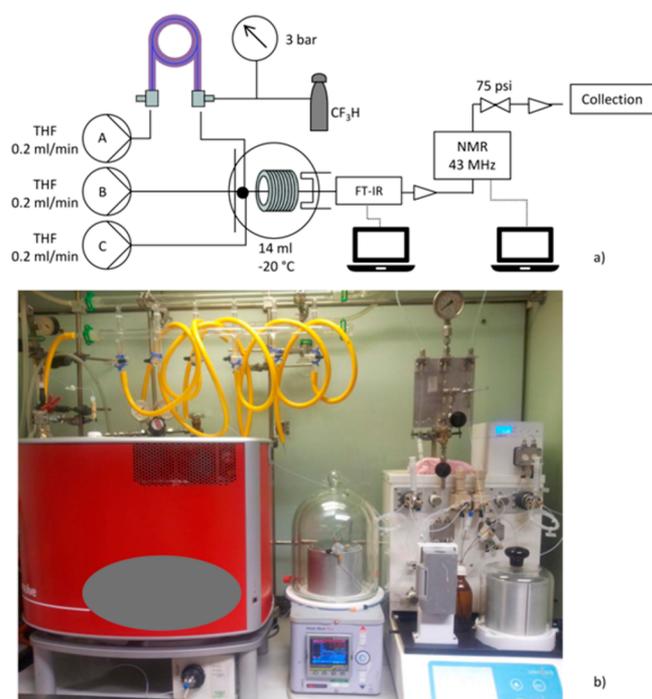
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The generation of the carbanion from trifluoromethane by deprotonation has been extensively investigated and numerous reports on the lifetime of this intermediate suggest that it is prone to rapid fluoride atom loss and conversion into the extremely reactive difluorocarbene intermediate.<sup>57–62</sup> Despite the increasing interest in the cost-efficient and sustainable use of  $\text{CF}_3\text{H}$  as trifluoromethylating reagent, there are still concerns relating to its clean applications and interception in organic synthesis programs.

Here we describe a continuous chemical approach for the use of  $\text{CF}_3\text{H}$  as a source of trifluoromethanide anion, and its direct use as a nucleophile to react with a range of carbonyl compounds and chlorosilanes. We demonstrate the practical benefits derived from the introduction of the Fourier transform infrared (FT-IR) and the nuclear magnetic resonance (NMR) in-line analytic tools for the accurate dosing of  $\text{CF}_3\text{H}$  gas and the quantitative trapping of the highly reactive and unstable trifluoromethanide anion intermediate.

## RESULTS AND DISCUSSION

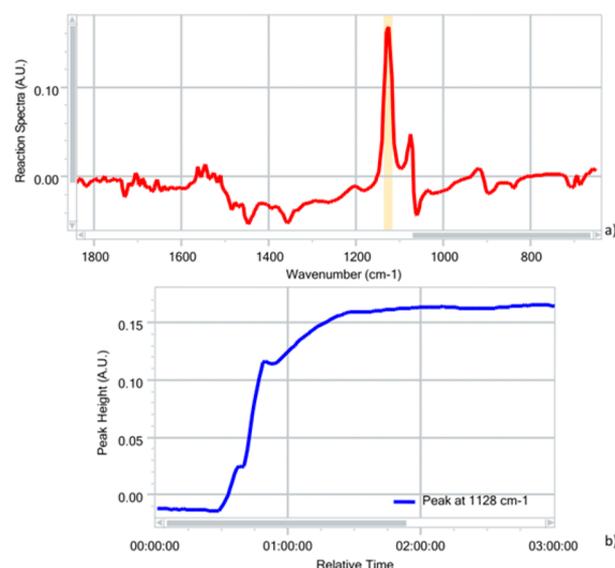
A first screening of conditions highlighted that the temperature, residence time, pressure, and mixing were all crucial reaction parameters. The process setup was particularly pivotal to reach the optimum reagent stoichiometry and avoid collateral reactions due to the decomposition of the trifluoromethanide anion (Figure 1a). A four-way cross connection valve for high pressure was installed to allow efficient mixing of the three reaction streams (flow rate 0.2 mL/min each) containing respectively the base, the electrophile, and the  $\text{CF}_3\text{H}$  solution. The resulting mixture was then passed through a PTFE coil reactor (14 mL). Both the mixing zone and the reaction zone were maintained at a controlled temperature ( $-20\text{ }^\circ\text{C}$ ) by using



**Figure 1.** (a) Schematic of the flow reactor setup using three pumps ( $\text{FR}_A = \text{FR}_B = \text{FR}_C = 0.2\text{ mL/min}$ ), a tube-in-tube reactor (1.0 m of AF-2400 tubing), a PTFE coil reactor (14 mL), a cooling device ( $-20\text{ }^\circ\text{C}$ ), a FT-IR instrument, and a benchtop NMR machine (43 MHz), a back pressure regulator (75 psi). (b) Picture of the apparatus.

a cooling device (Polar Bear Plus from Cambridge Reactor Design). The gas was introduced into the system using the tube-in-tube reactor, which is reported as a simple and efficient method to afford homogeneous solutions of reactive gases in flow (Figure 1b).

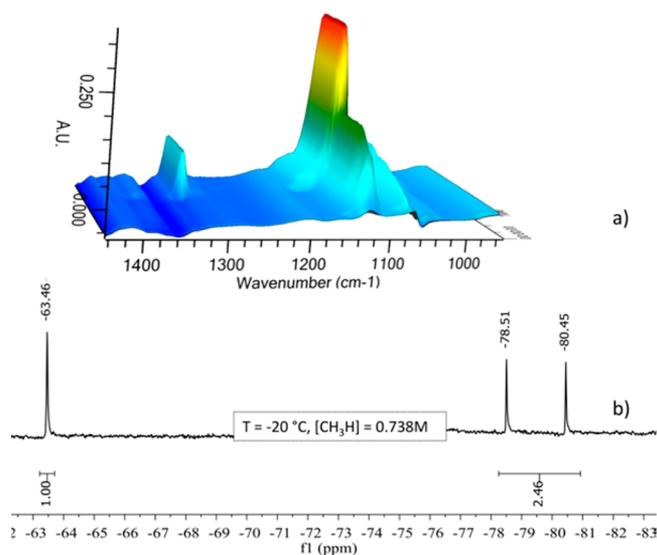
First, it was verified that the Teflon AF-2400 membrane of the inner tube, containing tetrahydrofuran (THF), was permeable to  $\text{CF}_3\text{H}$ . For this purpose, an in-line FT-IR instrument (FlowIR from Mettler Toledo) was used and the signal at  $1128\text{ cm}^{-1}$  was monitored (Figure 2a) until the steady state was reached (Figure 2b).



**Figure 2.** (a) In-line FT-IR monitoring. (b) Trend of the signal at  $1128\text{ cm}^{-1}$  assigned to  $\text{CF}_3\text{H}$ .

Aiming to quantify the concentration of  $\text{CF}_3\text{H}$  in the efflux stream from the coil reactor ( $-20\text{ }^\circ\text{C}$ ), a solution of  $\alpha,\alpha,\alpha$ -trifluorotoluene ( $\text{PhCF}_3$ ) in THF (0.3 M) was used as internal standard and, thus, pumped through the stream C (flow rate 0.2 mL/min). The signal at  $1328\text{ cm}^{-1}$  in the corresponding FT-IR spectrum was monitored until the steady state was reached (Figure 3a). At this point a  $^{19}\text{F}$  NMR spectrum was recorded (Figure 3b), using the in-line benchtop NMR machine (43 MHz, Spinsolve from Magritek) installed soon after the in-line FT-IR device. Comparing the integral values of the signals assigned respectively to  $\text{PhCF}_3$  (singlet at  $-63.46\text{ ppm}$ ) and to  $\text{CF}_3\text{H}$  (doublet at  $-79.49\text{ ppm}$ ), it was determined the concentration of the gas dissolved in the solution under these conditions, equated to 0.738 M.

Once the exact amount of  $\text{CF}_3\text{H}$  in the reaction mixture was known, we could then optimize the concentrations of the other reagents involved in the  $\text{CF}_3\text{H}$  deprotonation/electrophile trapping sequence. The activation of fluoroform with potassium bis(trimethylsilyl)amide (KHMDS) and addition of the formed trifluoromethanide anion to carbonyl compounds in batch mode was described by Prakash et al. The resulting fluorinated products were obtained with modest to good yields (10–81% yields), depending on the substrates.<sup>60</sup> The addition of  $\text{CF}_3\text{H}$  was realized by bubbling the gas into the reaction mixture over different times and with different flow rates. Aiming to demonstrate the importance of the accurate dosing of  $\text{CF}_3\text{H}$  on the productivity of the reaction, a screening of the optimum reagent concentrations was conducted, using KHMDS as a base



**Figure 3.** (a) In-line FT-IR monitoring of the signals respectively at  $1128\text{ cm}^{-1}$  ( $\text{CF}_3\text{H}$ ) and at  $1328\text{ cm}^{-1}$  ( $\text{PhCF}_3$ ). (b) In-line  $^{19}\text{F}$  NMR spectrum of the solution containing  $\text{PhCF}_3$  as internal standard ( $-63.46\text{ ppm}$ ) and  $\text{CF}_3\text{H}$  ( $-79.49\text{ ppm}$ ).

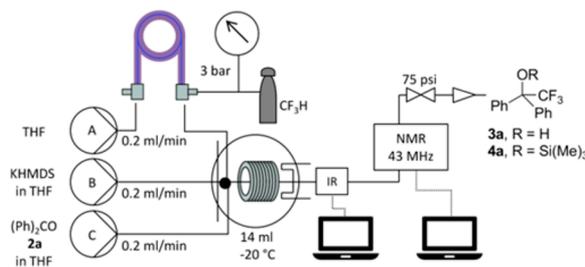
with benzophenone **2a** as an electrophile (Table 1). When an excess of  $\text{CF}_3\text{H}$  (2.46 equiv) was reacted with benzophenone (1.0 equiv) and KHMDS (1.16 equiv), the alcohol **3a** was obtained smoothly (93% conversion) in 30 min (Table 1, entry 1). When the concentration of the electrophile and the base were both increased (1.0 M), keeping constant the concentration of  $\text{CF}_3\text{H}$  (0.738 M), full conversion to the alcohol **3a** was observed (Table 1, entry 2; conversion 99%). Interestingly, the formation of *O*-protected alcohol **4a** was detected when an excess of base was used with respect to benzophenone and  $\text{CF}_3\text{H}$ . Increasing the concentration of KHMDS led to increased formation of **4a** (Table 1, entries 3–4). Bis-(trimethylsilyl)amine (HMDS), which is formed during the deprotonation step of  $\text{CF}_3\text{H}$  by KHMDS, is reported to be a weak trimethylsilyl donor. In an effort to study its role in the formation of the trimethylsilyl ether **4a**, HMDS (0.8 M) was added to the reaction mixture. In this case a selective formation

of **3a** was observed, together with only traces (0.1%) of **4a** (Table 1, entry 5). By contrast, the trimethylsilyl ether **4a** was formed exclusively when a strong trimethylsilyl donor, such as chlorotrimethylsilane (TMSCl), was used as additive (Table 1, entry 6). Literature data from magnetic resonance experiments of KHMDS suggest it exists in THF solution as a polymeric THF-solvate  $[(\text{KHMDs})_2(\text{THF})_2]_\infty$  where molecules of solvent can be displaced by Lewis donors, causing the monomerization of the complex.<sup>63</sup> It is likely that when an excess of KHMDS is present in the reaction mixture, a polymeric THF-solvate  $[(\text{KHMDs})_2(\text{THF})_2]_\infty$  exists and, spontaneously, leads to the transfer of the trimethylsilyl moiety to oxygen, due to a proximity effect. The presence of HMDS could then cause the decomplexation of the polymeric THF-solvate.

The real-time  $^{19}\text{F}$  NMR monitoring provided important information concerning the reaction progress under the conditions described in Table 1, entry 3, where a mix of **3a** and **4a** (ratio 58:42) was observed in the crude reaction mixture. According to the NMR spectra recorded in-line, compound **4a** should be generated first (Figure 4b). The formation of the alcohol **3a** is delayed with respect to **4a** and could be ascribed to the progressive decomplexation of the polymeric THF-solvate  $[(\text{KHMDs})_2(\text{THF})_2]_\infty$  induced by the formation of HMDS during the  $\text{CF}_3\text{H}$  deprotonation. This would give rise to the gradual formation of **3a** (see Table 1, entry 5). Also the hypothesis of a progressive cleavage of the trimethylsilyl group from **4a** was taken into account, whereby the fluoride anion, derived hypothetically from the decomposition of the trifluoromethanide anion, would be responsible. According to this explanation, fluorotrimethylsilane (TMSF) would be formed simultaneously (Figure 4a). However, no signal in the  $^{19}\text{F}$  NMR spectra could be assigned to this compound (Figure 4b).

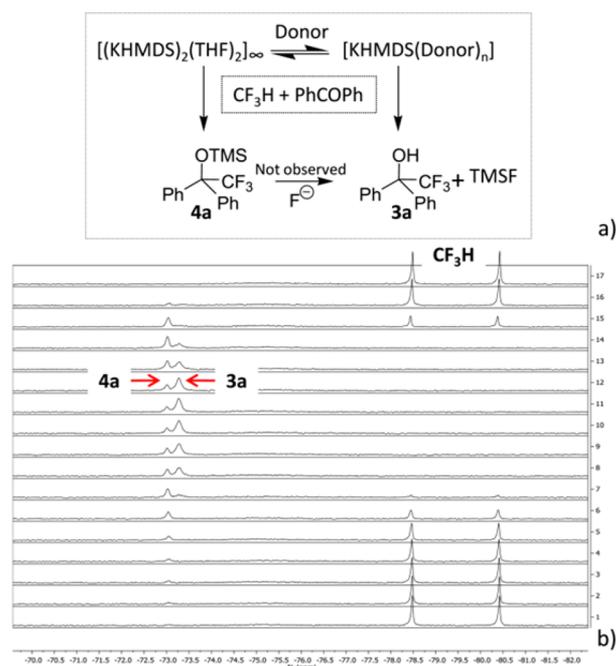
The protocol which has been developed for the generation of trifluoromethyl carbanion and its in situ trapping with benzophenone (Table 1, entry 2) was beneficial with respect to the corresponding batch method,<sup>60</sup> in terms of reaction time (23 min vs 12 h), accurate control of  $\text{CF}_3\text{H}$  dosing, productivity (4.6 vs 0.225 mmol/h), and more importantly, complete consumption of the  $\text{CF}_3\text{H}$  used in the process.

**Table 1.** Screening of the Optimum Reagent Concentrations during the Trifluoromethyl Carbanion Generation and In Situ Trapping with Benzophenone **2a**<sup>a</sup>



entry	[ <b>2a</b> ], M	[KHMDS], M	[ $\text{CF}_3\text{H}$ ], M	[additive], M	ratio <b>3a</b> : <b>4a</b>	conversion, %
1	0.3	0.35	0.738	none	100:0	93
2	1.0	1.0	0.738	none	100:0	99
3	0.3	1.0	0.738	none	58:42	99
4	0.15	1.0	0.738	none	29:71	99
5	0.3	1.0	0.738	HMDS, 0.8	99.9:0.1	71
6	0.3	1.0	0.738	TMSCl, 0.3	0:100	37

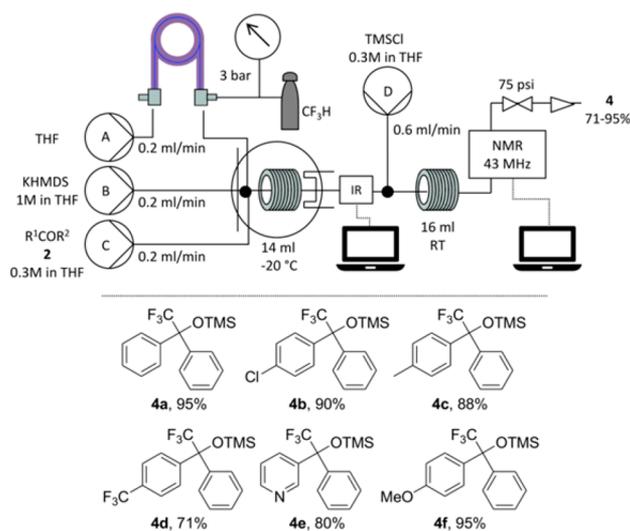
<sup>a</sup>Conversions were determined by NMR, using  $\text{PhCF}_3$  as internal standard.



**Figure 4.** (a) Possible reaction pathways of trifluoromethane ( $\text{CF}_3\text{H}$ ) with benzophenone ( $\text{PhCOPh}$ ) in the presence of  $\text{KHMDs}$ . (b) In-line  $^{19}\text{F}$  NMR monitoring of the reaction mixture over the time containing **4a** (at  $-73.06$  ppm), **3a** ( $-73.30$  ppm), and  $\text{CF}_3\text{H}$  ( $-79.49$  ppm).

The insertion of a fourth stream containing a solution of  $\text{TMSCl}$  in  $\text{THF}$  ( $0.3$  M; pump D: flow rate  $0.6$  mL/min; [Chart 1](#)) and the introduction of an additional PTFE coil reactor ( $16$  mL) permitted the in-line derivatization of the alcohols **3**, and therefore gave access to a number of substituted trimethylsilyl ethers **4a–4f** with excellent yields (isolated yields after chromatographic purification  $71$ – $95\%$ ) and in a relatively short time ( $1.15$  h).

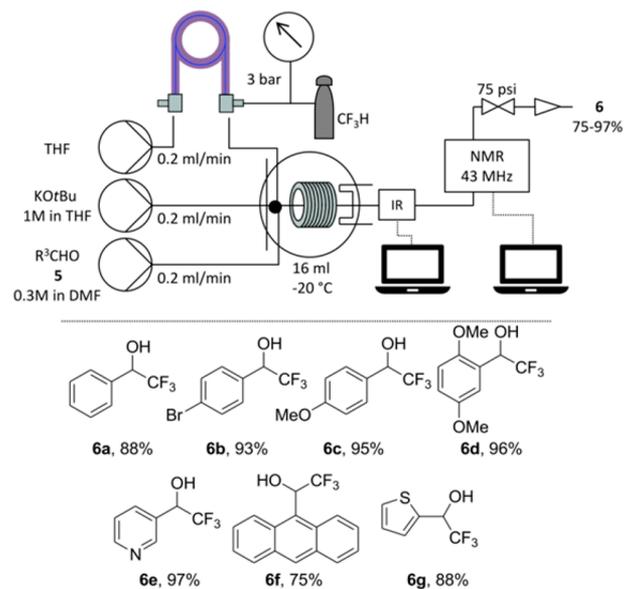
**Chart 1.** Synthesis of *O*-Trimethylsilyl Fluorinated Ethers **4a–4f** by an Intensified Process (Trifluoromethanide Carbanion – Nucleophilic Addition to Ketones **2a–2f** – Product Derivatization) with In-Line FT-IR and NMR Monitoring



Next, the preparation of trifluoromethyl carbinols **6a–6g** starting from a number of aldehydes was explored. Shibata et al. reported on the use of sterically hindered organo-superbases to stabilize the naked trifluoromethanide carbanion and enable the trapping with aldehydes.<sup>59</sup> Aiming to develop a more sustainable process for large-scale production, we investigated the use of a less expensive non-nucleophilic strong base (weaker than amide bases), such as potassium *tert*-butoxide (*t*-BuOK). While this reaction is reported to perform well in dimethylformamide (DMF), which acts as trifluoromethanide reservoir,<sup>64</sup> the conversion to the corresponding fluorinated products occurs in modest yields when the same reaction is performed in pure  $\text{THF}$ .<sup>60</sup>

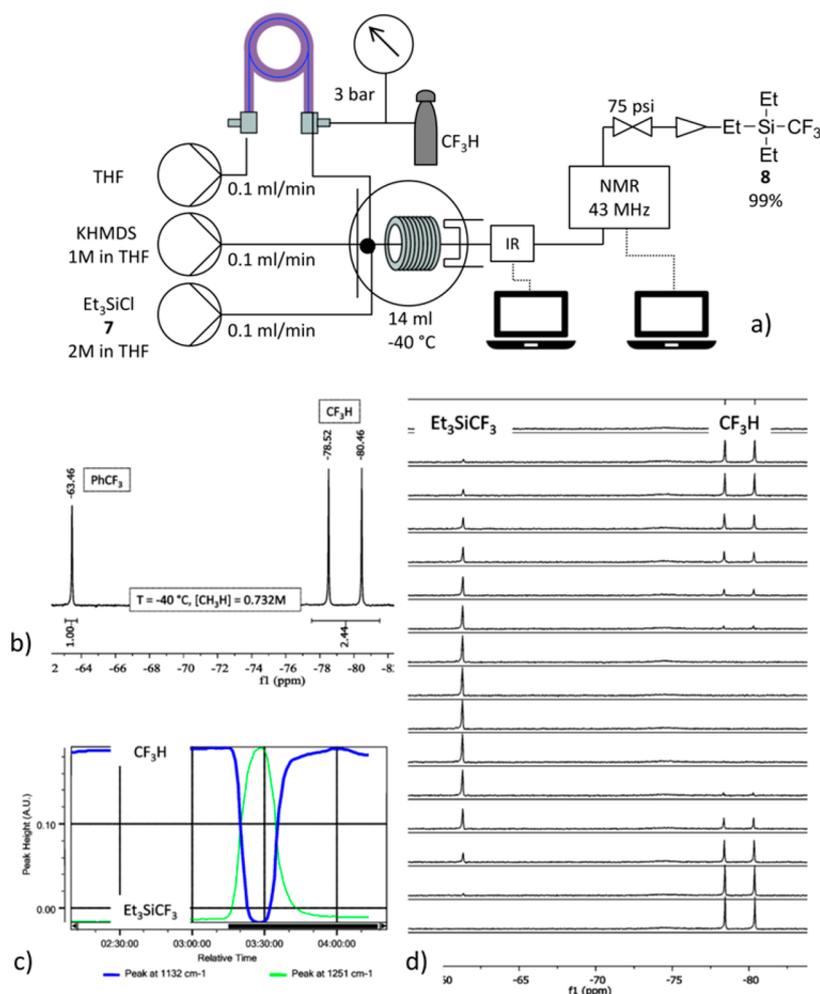
Similar moderate results were obtained when a mixture of  $\text{CF}_3\text{H}$ , *t*-BuOK, and benzaldehyde **5a** was reacted in flow, using the same flow setup developed for the nucleophilic trifluoromethylation of the ketones **2**. A screening of the reaction conditions and the process design demonstrated that a noticeably improved result could be obtained when a solution of aldehyde **5** in DMF ( $0.3$  M) was mixed at  $-20$  °C with two streams containing respectively  $\text{CF}_3\text{H}$  ( $0.738$  M in  $\text{THF}$ ) and *t*-BuOK ( $1.0$  M in  $\text{THF}$ ). The resulting mixture, reacting at  $-20$  °C within a PTFE reactor coil ( $16$  mL, residence time  $27$  min), gave the corresponding fluorinated carbinols **6a–6g** with excellent results ([Chart 2](#); yields after chromatographic

**Chart 2.** Synthesis of Fluorinated Carbinols **6a–6g** via Generation of Trifluoromethanide Carbanion and In Situ Trapping with Aldehydes **5a–5g** with In-Line FT-IR and NMR Monitoring



purification  $75$ – $97\%$ ). Importantly, the real-time  $^{19}\text{F}$  NMR monitoring confirmed that no fluorinated byproduct was formed under these reaction conditions and that complete consumption of  $\text{CF}_3\text{H}$  was achieved.

Finally, we extended our study to the development of a continuous scalable production of fluorinated organosilicon compounds, which are extensively applied in organic synthesis as fluoroalkylation reagents.<sup>65</sup> There is a growing interest in developing more environmentally benign methods for their large-scale production, which would circumvent the use of the ozone-depleting bromotrifluoromethane ( $\text{CF}_3\text{Br}$ ) as starting



**Figure 5.** (a) Schematic of the flow reactor setup for the synthesis of trifluoromethyltriethylsilane **8** using three pumps ( $FR_A = FR_B = FR_C = 0.1$  mL/min), a tube-in-tube reactor (1.0 m of AF-2400 tubing), a PTFE coil reactor (14 mL), a cooling device ( $-40$  °C), a FT-IR instrument, and a benchtop NMR machine (43 MHz). (b) In-line <sup>19</sup>F NMR spectrum of the solution containing PhCF<sub>3</sub> as internal standard ( $-63.46$  ppm) and CF<sub>3</sub>H ( $-79.49$  ppm) at  $-40$  °C. (c) In-line FT-IR analysis by monitoring the trend of CF<sub>3</sub>H and Et<sub>3</sub>SiCF<sub>3</sub>. (d) In-line <sup>19</sup>F NMR analysis by monitoring the trends of CF<sub>3</sub>H and Et<sub>3</sub>SiCF<sub>3</sub>.

material.<sup>66</sup> In particular, we turned our efforts to the preparation of trifluoromethyltriethylsilane **8**, which is widely used as a trifluoromethyl precursor.<sup>67,68</sup> The reaction conditions were accurately investigated, taking advantage of the real-time monitoring of the reaction mixture. It was found that a lower temperature ( $-40$  °C) and longer residence time (57 min) were crucial parameters to succeed in the formation of **8**. The concentration of CF<sub>3</sub>H in the solution under the new flow setup (Figure 5a;  $T = -40$  °C;  $FR_A = FR_B = FR_C = 0.1$  mL/min) was measured by using the in-line <sup>19</sup>F NMR analysis (Figure 5b;  $\alpha,\alpha,\alpha$ -trifluorotoluene as internal standard, 0.3 M; [CF<sub>3</sub>H] = 0.732).

The reaction was continuously monitored by FT-IR (Figure 5c) and by <sup>19</sup>F NMR (Figure 5d), discovering that an excess of chlorotriethylsilane (Et<sub>3</sub>SiCl, 2M), used as electrophile, was crucial to suppress the formation of triethylsilyl fluoride (Et<sub>3</sub>SiF; signal at  $-151.02$  ppm in the <sup>19</sup>F NMR spectrum) as byproduct. Under these reaction conditions, full consumption of CF<sub>3</sub>H was observed (Figure 5c, blue line, trend of the peak at  $1132$  cm<sup>-1</sup>; Figure 5d, disappearance of the doublet at  $-79.49$  ppm) and clean formation of compound **8** was detected (Figure 5d, green line, trend of the peak at  $1251$  cm<sup>-1</sup>; Figure 5d, appearance of the singlet at  $-61.44$  ppm).

## CONCLUSION

In conclusion, a synthetic approach which allows the safe utilization of a potent greenhouse gas, such as trifluoromethane, has been developed. With exploitation of the discovered permeability of the Teflon AF-2400 membrane to CF<sub>3</sub>H, a controlled introduction of this gas into the reaction mixture was achieved. The real-time spectroscopic analysis (FT-IR and NMR) enhanced the precise measurement of CF<sub>3</sub>H in the solution, with clearly benefits the selectivity in the products formation. The process described was fully contained and any possible dispersion of fluoromethane into the atmosphere was accurately controlled and minimized. The fast and complete interception of the trifluoromethyl carbanion intermediate by ketones, aldehydes, and chlorosilanes gave access to functional fluorinated products with high yields. The spontaneous decomposition of the trifluoromethyl carbanion intermediate to difluorocarbene was completely suppressed, resulting in simpler downstream processing. The successful production of trifluoromethyltriethylsilane, as trifluoromethylation reagent, also could extend applications of the flow reactor setup to the trifluoromethylation of enolizable carbonyl compounds, which were not suitable substrates in this work. The reactor design

and the real-time analytical tools adopted in this work could find application in other similar synthesis programs.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acssuschemeng.7b04012.

Synthetic procedures and characterization of compounds (PDF)

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### Author Contributions

The paper was written through contributions of all authors. All authors have given approval to the final version of the paper.

### Notes

The authors declare no competing financial interest.

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