

AVT-340 Research Workshop on Preparation and Characterization of Energetic Materials

Employing Microfluidic Technology for the Production of Energetics

Dr. Thorsten Schroer, AFRL/RQRP, United States

3 February 2021

Outline

- **Historical Background**
- **The Advantages of Microfluidics**
 - ◆ **Heat Management in Micro-Reactors**
 - ◆ **Mixing in Micro-Reactors**
- **Optimization of the Production of Nitrate Esters in Micro-Reactors**
- **Scaling the Process**

Acquisition of Energetic Ingredients in the 21st Century

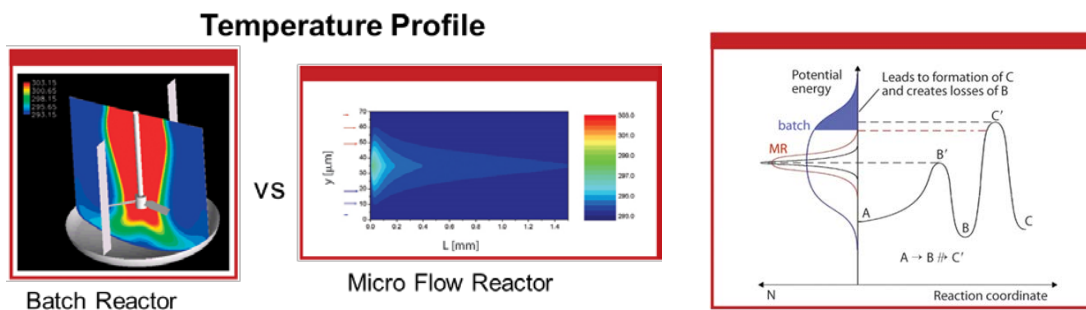
- ◆ Deteriorating industrial base makes it more and more difficult to acquire energetic materials and their precursors
- ◆ Safety and environmental regulations make the production of new energetic ingredients in multi pounds quantities
 - ◆ too expensive for large business
 - ◆ (nearly) impossible for small business
- ◆ Development takes an extremely long time, even for very promising ingredients (e.g. CL-20)

In order to address this problem, smarter ways to produce energetic materials have to be developed!

History

- 1940** First example of a microfluidic, thin layer electrophoretic separation device described by J. S. L. Philpot (*Trans. Faraday Soc.* **1940**, 35, 38-46.)
- 1986** Early studies of microstructured reactors performed by scientists of the former GDR. Theoretical consideration were never put into practical application (W. Löhder, L. Bergann German Patent DD 246 257 A1)
- 1989** First microreactors were designed and placed in operation at the Karlsruher (Nuclear) Research Center, Germany. Reactors were used for uranium enrichment (K. Schubert et. al., *Microscale Thermophys. Eng.* **2001**, 5, 17-39.)
- 1995** Wide development of this technology started after workshop in Mainz, Germany
- 2010** Micro-reactors are employed for the continuous synthesis of nitrate esters (T. Tuerke, A. Mendel, D. Boskovic, S. Loebbecke, Proceed. 41th Int. An. Conf. 2010 ICT, Karlsruhe)

Heat Control in Microfluidic Reactors



High Area : Volume Ratio significantly improves Heat Transfer

- ◆ Reaction can be run isothermal without expensive heating / cooling
- ◆ Improved temperature control increases yields by enhancing the reaction efficiency and reducing the amounts of by-products and solvent
- ◆ Reduced probability of catastrophically run-away reaction
- ◆ Enables the scale-up of highly exothermic processes which cannot be controlled in a batch reactor
- ◆ Reaction parameter scale with reactor size as long as the reactor diameter stays constant; no re-optimization like in a batch reactor is necessary

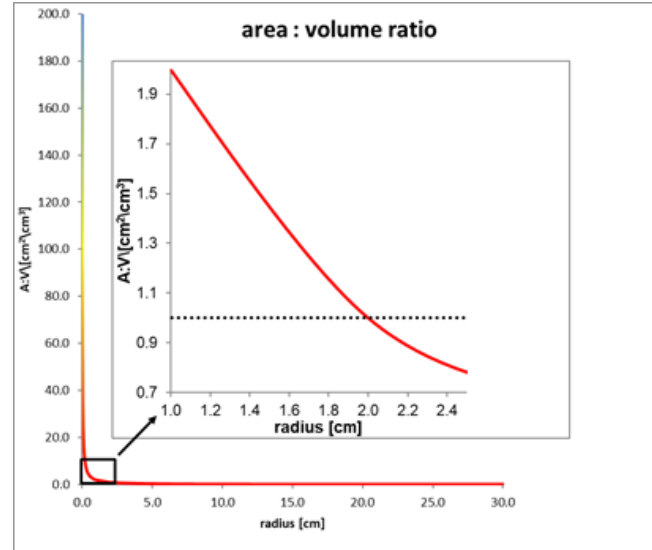
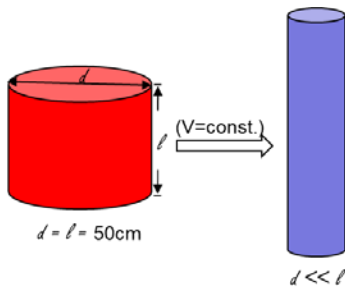
If you Can't
Stand the
Heat, Get Out
of the Flask

K. Jensen et. al.;
Angew. Chem., Int. Ed.
2011, 50, 7502-7519

Process can be performed at the temperature
necessary to activate the reaction

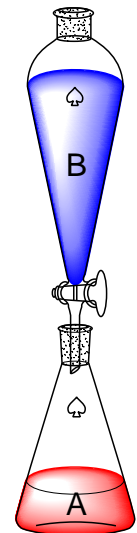
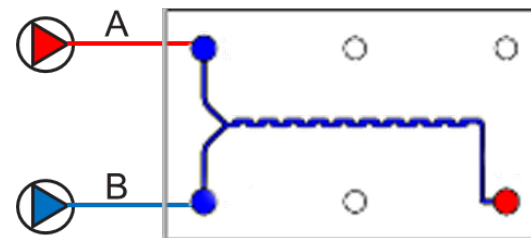
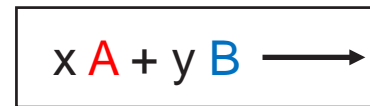
Why Microfluidics ? Mixing

“Stretching” of a 100L Batch Reactor



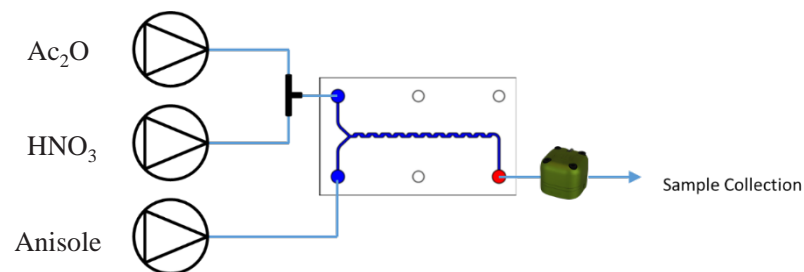
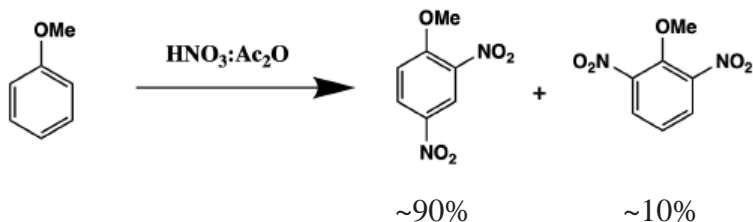
The volume of a micro-reactor can be much smaller compared to a batch reactor because

- ◆ Reaction are always performed in the right stoichiometry with the minimum amount of solvent
- ◆ Higher mass transfer due to higher mix efficiency
- ◆ Larger amounts are obtained by continuous operation

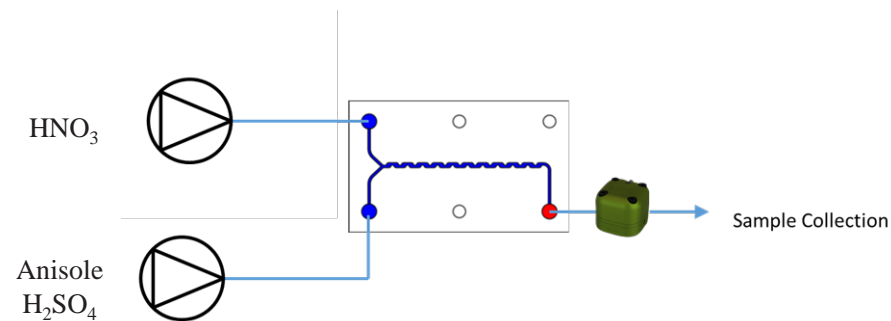
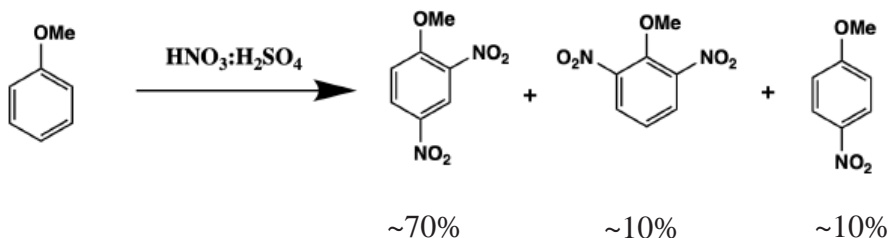


Microfluidic Synthesis of 2,4-Dinitroanisole (DNAN)

Acetyl Nitrate Nitration

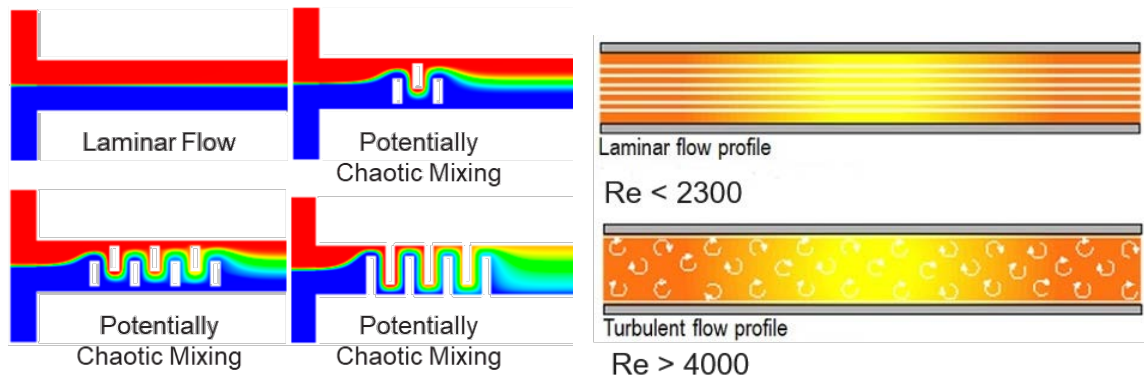


Mixed Acid Nitration



- ◆ Acetyl nitrate Nitration was performed at Holsten at larger scale (“We used a static mixer and the banging in the plant was horrendous at the point where the educator joined the streams right at the mixer!” *B. Sleadd*)
- ◆ ΔH_r of direct nitration of anisole -15 KJ/mol; $t_{50} \approx 5$ sec
- ◆ Very good yields using a 100 μL LTF reactor ($d < 1$ mm)

Laminar Flow vs Turbulent Flow vs Chaotic Mixing

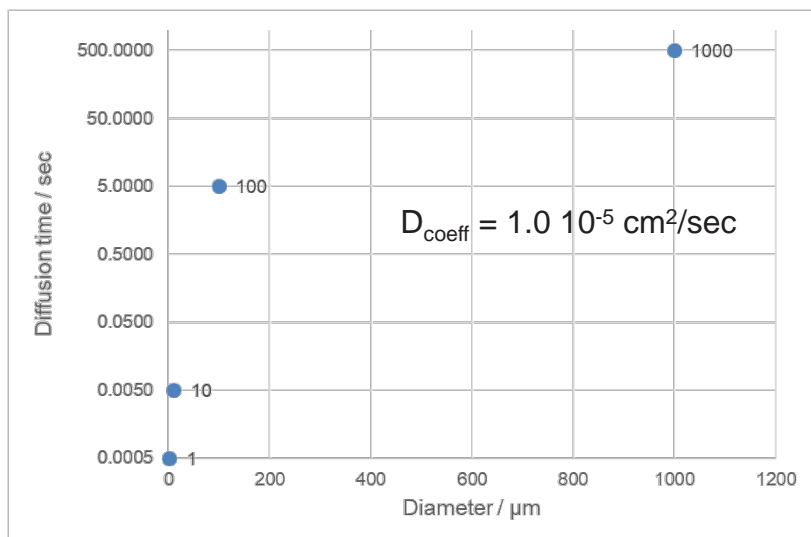


Reynolds Number

$$Re = \frac{\text{inertial (turbulent) forces}}{\text{viscous forces}} = \frac{VL}{\nu}$$

V = mean velocity
 L = traveled length
 ν = kinematic viscosity

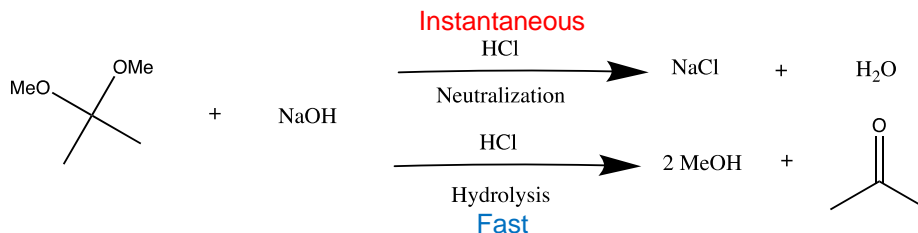
V. Rudyak et. al., *Micromachines* 2014, 5, 886.



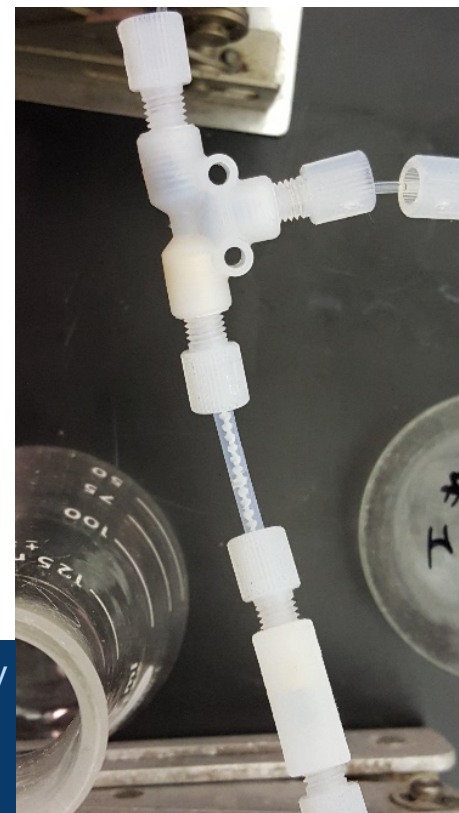
Turbulent flow / chaotic mixing is important for

- ◆ Increasing mass transfer e.g. reducing residence time
- ◆ Suppressing the formation of side / decomposition products
- ◆ Synthesizing the kinetically favored product

Bourne Reaction to Determine the Mix Efficiency



Microreactor Manufacturer	Mixer	X_{acetone} [50 mL/min]	P_1 [bar]	P_2 [bar]	ΔP [bar]
	S	0.30	1.2	0	1.2
Little Things Factory	ST	0.22	2.8	0	2.8
	X	0.56	1.9	0	1.9
	XL	0.48	4.1	0.5	3.6
IDEX	Tee Junction	0.15	1.7	0.1	1.6
Stamixco	Static Mixer	0.20	1.7	0.1	1.6

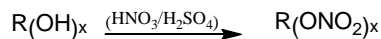


- ◆ In order to improve mixing efficiency in microreactors, extremely high flow rates are required.
- ◆ Expensive microreactors are not necessarily showing the highest mix efficiency!

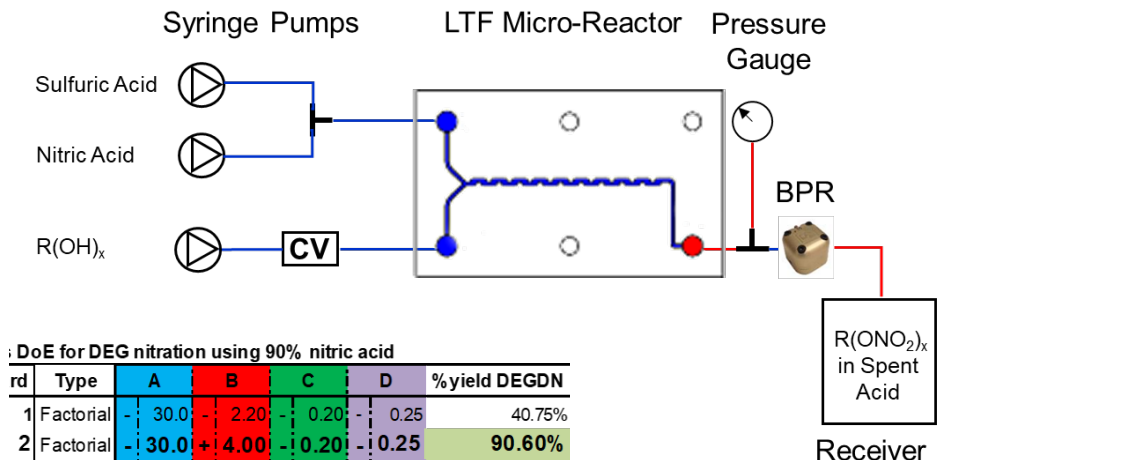
“Flow chemistry isn’t hard. Don't fall for the slick marketing campaigns and glossy brochures of the corporate vendors. Steer clear of their pricey equipment and exorbitant service contracts. If you do it yourself, you can get better results at a fraction of the cost. So put away your cheque book, roll up your sleeves, and give it ago.”

J. C. Mello, *Mater. Horiz.* **2014**, *1*, 373

Optimization of the Microfluidic Synthesis of Nitrate Esters



$R(OH)_x$	$R(ONO_2)_x$
<chem>OCCO</chem> ethylene glycol	<chem>OCC(=O)OCC(=O)O</chem> ethylene glycol dinitrate (EGDN)
<chem>OCCOCCO</chem> diethylene glycol	<chem>OCC(=O)OCCOCC(=O)O</chem> diethylene glycol dinitrate (DEGDN)
<chem>OCCOCCOCCO</chem> triethylene glycol	<chem>OCC(=O)OCCOCCOCC(=O)O</chem> triethylene glycol dinitrate (TEGDN)
<chem>OCC(O)CO</chem> glycerine	<chem>OCC(=O)OCC(O)CO</chem> glycerine trinitrate (NG)
<chem>OCC(O)CCO</chem> 1'2'4' butane triol	<chem>OCC(=O)OCC(O)CCO</chem> 1'2'4' butane trinitrate (BTTN)
<chem>CC(C)(O)CO</chem> 2' (hydroxymethyl) 2' methylpropane 1'3' diol	<chem>CC(C)(=O)OCC(=O)O</chem> 2' (nitrooxy)methyl 2' methylpropane 1'3' dinitrate (TMETN)
<chem>CC(C)(O)CO</chem> 2' (hydroxymethyl) 2' nitropropane 1'3' diol	<chem>CC(C)(=O)OCC(=O)O</chem> 2' (nitrooxy)methyl 2' nitropropane 1'3' dinitrate (NIBTN)

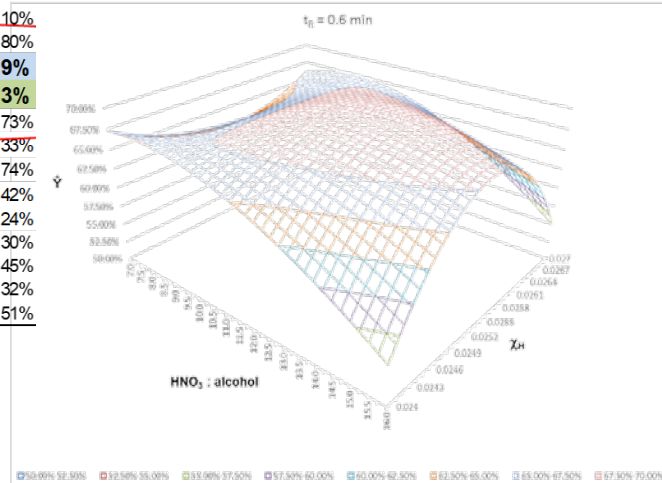


DoE for DEG nitration using 90% nitric acid

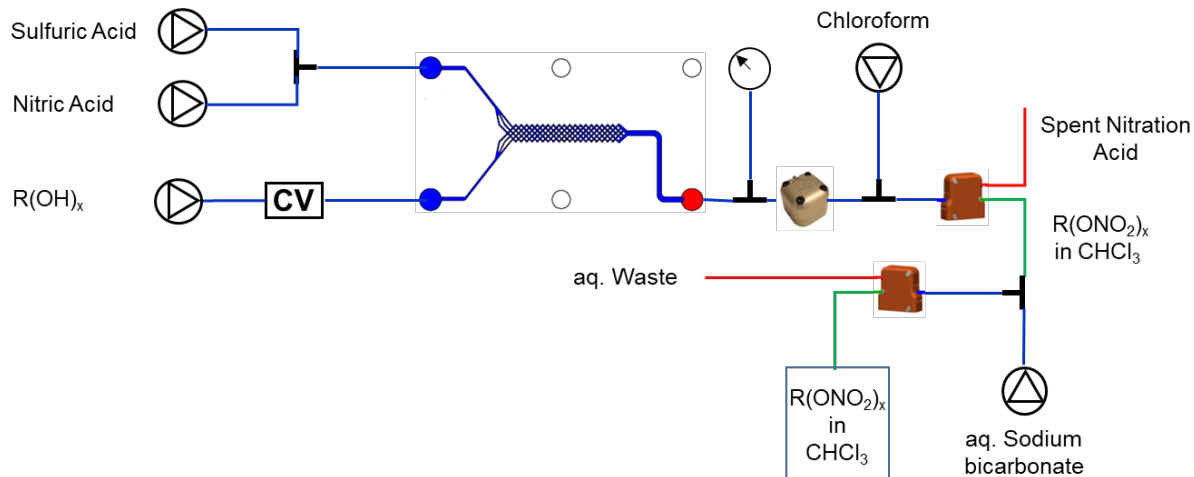
rd	Type	A	B	C	D	% yield DEGDN
1	Factorial	- 30.0	- 2.20	- 0.20	- 0.25	40.75%
2	Factorial	- 30.0	+ 4.00	- 0.20	- 0.25	90.60%
3	Factorial	- 30.0	- 2.20	+ 1.00	- 0.25	77.46%
4	Factorial	- 30.0	+ 4.00	+ 1.00	- 0.25	76.98%
5	Factorial	- 30.0	- 2.20	- 0.20	+ 0.75	76.98%
6	Factorial	- 30.0	+ 4.00	- 0.20	+ 0.75	30.01%
7	Factorial	- 30.0	- 2.20	+ 1.00	+ 0.75	89.10%
8	Factorial	- 30.0	+ 4.00	+ 1.00	+ 0.75	60.80%
9	Center	0 30.0	0 3.10	0 0.60	0 0.50	97.09%
10	Face	0 30.0	0 3.10	0 0.60	- 0.25	95.93%
11	Face	0 30.0	0 3.10	0 0.60	+ 0.75	96.73%
12	Face	0 30.0	0 3.10	- 0.20	0 0.50	74.33%
13	Face	0 30.0	0 3.10	+ 1.00	0 0.50	79.74%
14	Face	0 30.0	- 2.20	0 0.60	0 0.50	91.42%
15	Face	0 30.0	+ 4.00	0 0.60	0 0.50	92.24%
16	Side	0 30.0	- 2.20	- 0.20	0 0.50	25.30%
17	Side	0 30.0	- 2.20	+ 1.00	0 0.50	90.45%
18	Side	0 30.0	+ 4.00	- 0.20	0 0.50	89.32%
19	Side	0 30.0	+ 4.00	+ 1.00	0 0.50	83.51%

Design of Experiment

Reactive Surface Method



Prototype of the Microfluidic Nitrate Ester Production Process

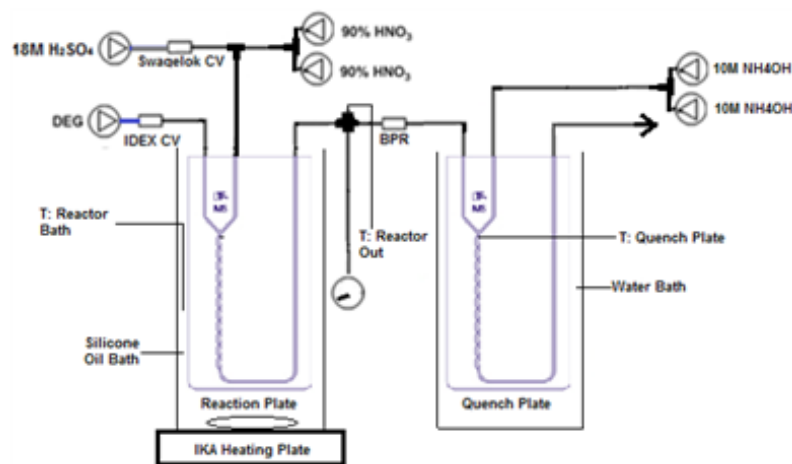


Implementation of reaction, isolation and purification in-flow modules allow for the synthesis, isolation and purification of the product in one flow process

Amounts of CHCl_3 and aq. NaHCO_3 necessary for isolation and purification optimized to minimize waste stream



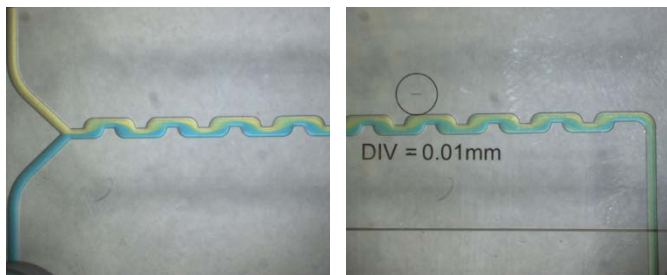
Scale up of Nitrate Ester Production Process



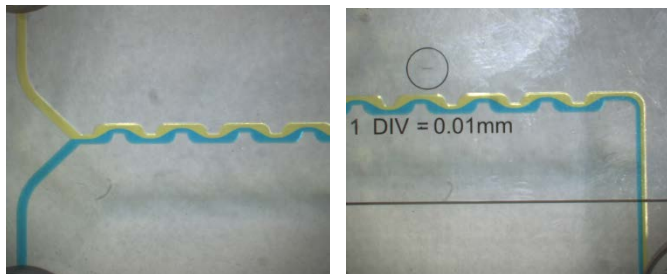
- ◆ First 10 g run successful; DEGDN yield 90%
- ◆ Check valves no longer closing properly => flow rates no longer adjustable
- ◆ Even check valve seals made from Kalrez 6380 cannot withstand nitric acid > 85% for a prolonged time
- ◆ Parker all Teflon valve compatible with 90% nitric acid but problems arose with 100% nitric acid



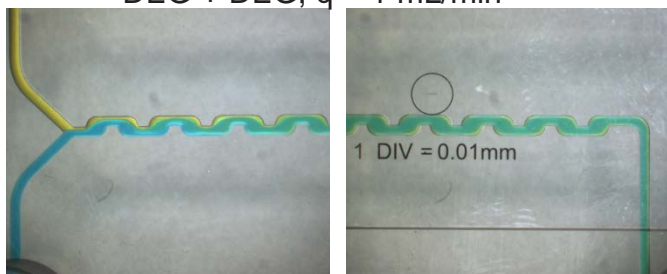
Problems with Material Compatibility and Viscosity



water + water; $q = 1 \text{ mL/min}$



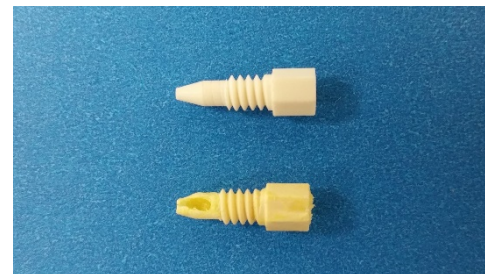
DEG + DEG; $q = 1 \text{ mL/min}$



water + DEG; $q = 1 \text{ mL/min}$

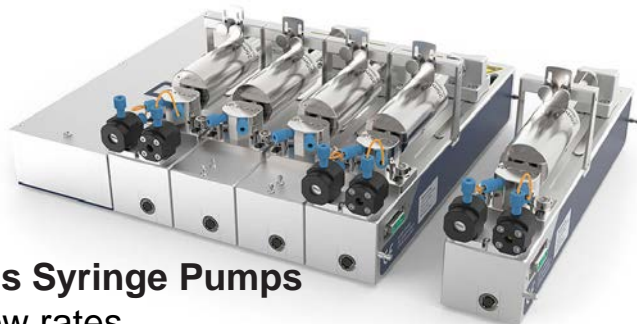
Viscosity has a profound influence on the mix efficiency of micro-reactors

Material	Density (g/cm^3)	dyn. Viscosity (cP)	kin. Viscosity (cSt)
water	1.0000	1.00	1.00
acetone	0.7850	0.30	0.38
ethanol	0.7890	1.07	1.36
methanol	0.7920	0.55	0.70
ether	0.7130	0.22	0.31
hexane	0.6550	0.30	0.45
chloroform	1.4900	0.52	0.35
diethylene glycol (DEG)	1.1180	35.70	31.93
triethylene glycol (TEG)	1.1250	49.00	43.56
glycerine	1.2600	950.00	753.97
diethylene dinitrate (DEGDN)	1.4100	8.10	5.74
triethylene dinitrate (TEGDN)	1.3300	13.20	9.92
nitroglycerine (NG)	1.5910	37.80	23.76
sulfuric acid 98%	1.8302	42.00	22.95
nitric acid 95%	1.4800	1.20	0.81



Not everything advertised to be compatible with 100% HNO_3 is necessarily compatible with 100% HNO_3

Finding the Right Pumps for Large-Scale Microfluidic Production Process



Continuous Syringe Pumps

- ◆ High flow rates
- ◆ Too many check valves; compatibility problems with 90%+ HNO₃
- ◆ Problems pumping highly viscous solutions



Titanium HP Pumps

- ◆ High flow rates
- ◆ Compatible with 90%+ HNO₃
- ◆ In case of highly viscous solutions flow rates have to be re-calibrated

Dampened Peristaltic Pumps

- ◆ Flow rates so far limited to 10 mL/min
- ◆ Compatible with 90%+ HNO₃
- ◆ Problems pumping highly viscous solutions



Best Solution!

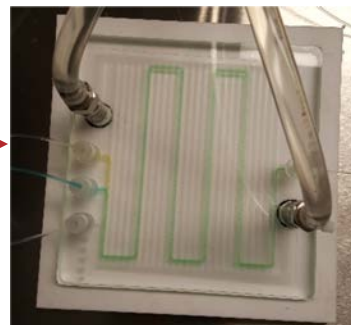
Scaling the Separation Modules

- ◆ First production runs were performed at the 50 g DEGDN level utilizing a 2 mL Little Things Factory reactor to proof the scalability of microfluidic processes.
- ◆ The same yields were obtained when the flow rates were increased by the same factor as the reactor
- ◆ However, scaling the separation and purification part of the reactor is not that easy

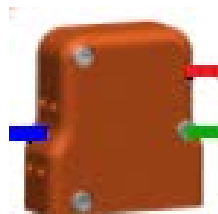


100 μ L LTF reactor

reaction
scales with
size of the
reactor

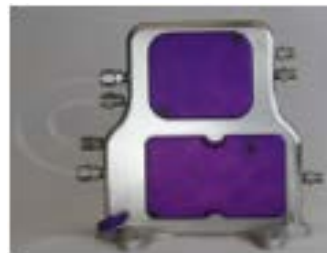


2 mL LTF reactor



Zaiput SEP 10 separator
(up to 12 mL/min)

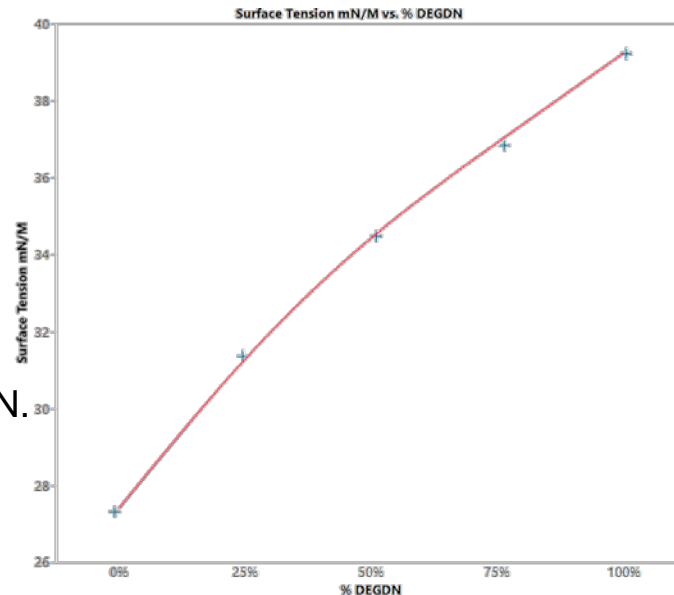
Separation
does not
scale with
the total flow
rate



Zaiput SEP 200 separator
(20 -200 mL/min)

Problems with the Zaiput in-flow Membrane Separators

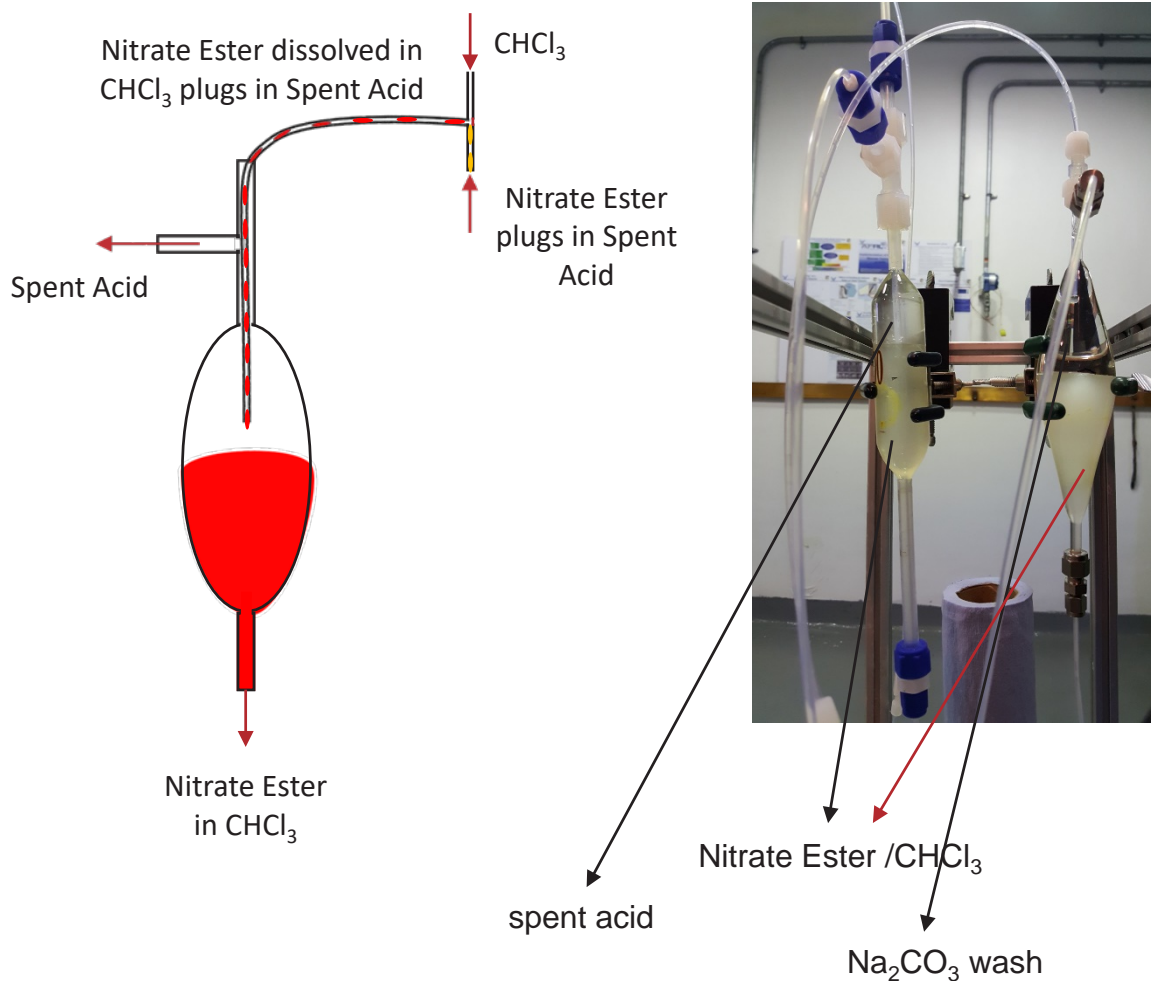
- ◆ Separation efficiency of the membranes depends on
 - ◆ the flow rates of the phases,
 - ◆ the viscosity of the phases,
 - ◆ the interaction between phases,
 - ◆ the interaction between phases and the membrane
 - ◆ and the pore size of the membrane.
- ◆ Surface tension of a DEGDN / chloroform solution changes considerable whit the mole fraction of DEGDN.
- ◆ Separators are optimized for phase viscosities up to 2 cps. Viscosities of spent acid (up to 20 cps) and DEGDN/ CHCl_3 solution ($\eta_{(\text{DEGDN})} = 8.1 \text{ cps @ } 20^\circ\text{C}$) are much higher.
- ◆ Up to 10% of DEGDN remains in the spent acid after in-flow extraction with chloroform. Second extraction step necessary.
- ◆ Formation of gases, like in the Na_2CO_3 neutralization, makes separation impossible.



Zaiput SEP 200 separator
(20 -200 mL/min)

**Alternative in-flow separation methods
have to be developed**

Gravimetric In-Flow Separators



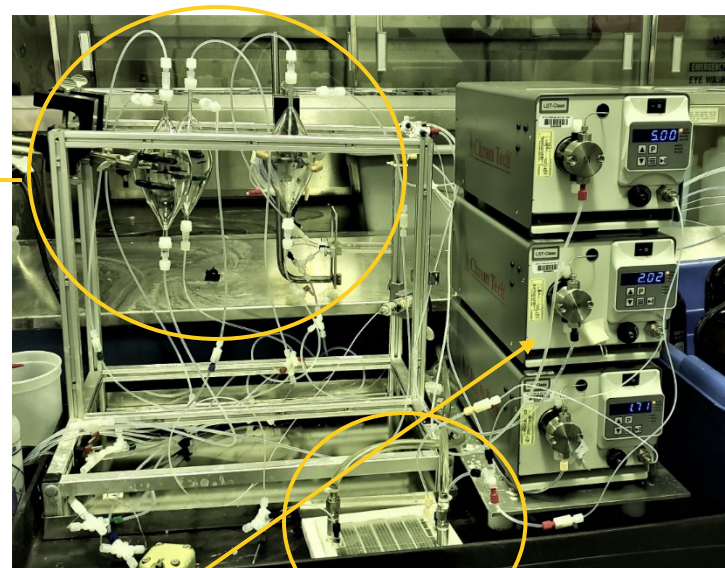
- ◆ Gravimetric in-flow separation based on methods described by S. Ley et. al.
- ◆ Nitrate ester / spent acid mixture extracted with CHCl_3 .
- ◆ Two phase system is collected in 100 mL gravimetric separator.
- ◆ Nitrate ester / CHCl_3 phase is pumped out of the separator at a slightly higher flow rate as CHCl_3 is added to nitrate ester / spent acid mixture.
- ◆ Spent acid overflows at top of separator into waste collection vessel.
- ◆ Same principal is applied for Na_2CO_3 neutralization step.

Steven Ley et. al., *Organic Letters* **2012**, 14, 4246.

Microfluidic Reactor for the Production of Nitrate Esters; “Final” set up

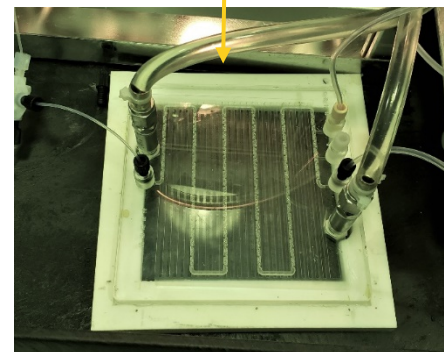
- ◆ HPLC pumps were acquired to substitute peristaltic pumps
- ◆ Greatly improves the reliability of the production of nitrate esters
- ◆ Micro-reactor can produce any nitrate ester on-demand.
- ◆ Production can be switched between different nitrate esters in a matter of minutes

Gravimetric Separators
for purification and
isolation of nitrate esters



Reactor

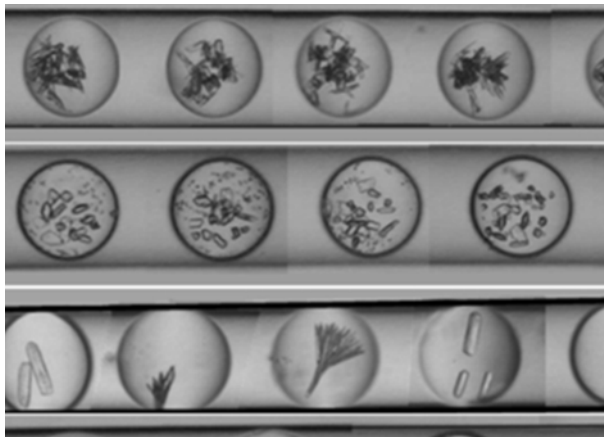
HPLC pumps for
alcohol, HNO_3
and H_2SO_4



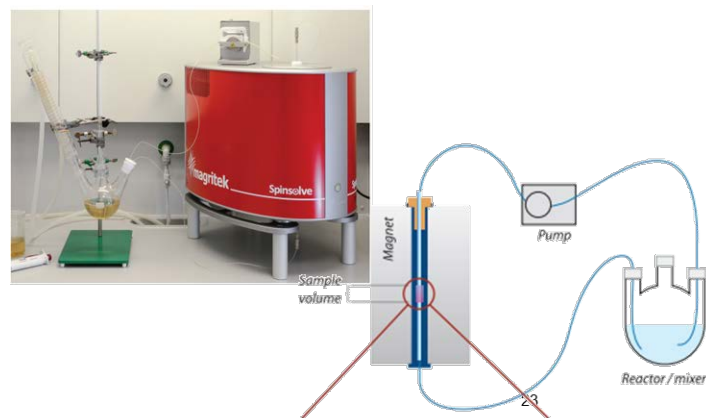
Outlook

Development of Microfluidic Technology will be Extended to

- ◆ Design of Various Micro-Synthesis and Processing Modules
- ◆ In-flow Analytical Probes for Process Optimization & Control
- ◆ Implementation of Software Tools for the Remote Operation of the Microfluidic Production of Energetics



Continuous flow crystallization in water bubbles imbedded in a per-fluorinated carrier oil (S. Veesler et. al., Org. Process Res. Dev. 2015)



The AFRL Microfluidic Team



2nd Lt Joshua Bonvissuto
Mr. Miguel Aguila
Dr. Gregory Ethan LeCroy
Ms. Mayra Rodriguez
Mr. Guillermo Ramirez
Mr. Tyler Downard
Dr. Brianna MacLeod



AFRL/RQR 



CCDC AC, Picatinny Arsenal, Drs.
Alexander Paraskos & Edward Cook

ARAP, Mr. Dale Ormond
EEE, Dr. Suhithi Peiris
JEMTP, Mr. Anthony Di Stasio

Questions