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PNNL-30107

Brief Update on Advancements by Commercial Vendors/Options for Feeding and Pumping Biomass Slurries for Hydrothermal Liquefaction

July 2020

Alan H Zacher
Andrew J Schmidt

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary of Findings and Future Considerations

This section distills out the findings and research of note to serve as an extended abstract of the results from this literature search.

Water Boundary-Layer for Lubrication and Solids Prevention in Hydrothermal Liquefaction

We recommend investigating the utility of adding a thin water boundary layer to the biomass feed lines for hydrothermal liquefaction (HTL). This may reduce line friction; decrease solids agglomeration and overcooking; and improve heat transfer, detailed in Section 2.4.2.

Potential Value of Deliberate Feed Pulsation

Slow, smooth pulsations in the HTL process liquid may improve heat transfer, mixing, and prevent solids segregation in process lines. This is based on Aarhus research detailed in Section 5.1 and could be implemented at commercial scale by modifying pulsation control software detailed in Sections 2.1.1 and 2.4.1.

Overpressure Delivery Considerations for Demonstration or Commercial Scale

There is a potential that the required minimum pump delivery pressure may need to be larger than initially assumed, particularly at demonstration and commercial scale due to line friction losses over distance between commercial unit operations. These losses may be considerable depending on the slurry, the piping diameter, and the distance flowed at sub-operating temperatures. This is based on various manufacturer literature, which is partly addressed by items such as line lubrication detailed in Section 2.4.2.

FELUWA Reporting Increased Maximum Pressure on Hose-Diaphragm Pumps

FELUWA raised the hose-diaphragm pump maximum pressure to 350 bar (up from 320 bar) and is potentially considering pressures as high as 500 bar although potentially retracted; this is detailed in Section 2.2.2.

New Milton Roy Pumps That Can Achieve HTL Conditions

Milton Roy, which did not originally have compatible pumps, is now offering slurry pumps based on technology and size that may be more compatible with HTL feeding applications. They now offer a piston diaphragm process pump and a positive displacement pump that can achieve 400 to 700 bar and is detailed in Section 3.16.

Few Significant New Announcements of High-Pressure High-Temperature Biomass Applications by Major Manufacturers

Searching through press releases between 2011 and 2019, there did not appear to be high-pressure biomass applications that could be easily related to biomass feeding to HTL. There continues to be interest in lower-pressure bio-solids handling. No evidence was found regarding pump selection or development within the pump original equipment manufacturers evaluated that suggests public relationships with HTL commercialization efforts worldwide.

New FELUWA Test Rig Available for Customer Feed Evaluation

It was recently reported that FELUWA headquarters has a new test rig available for assessing customer feeds. The purpose is for pumping evaluation and wear analysis; this discussion is found in Section 2.2.1.

Wier Mineral Updated Pump Test Facility

Weir reported in March 2019 that their Specialty Pump Test Facility has been updated and is available for pump trials for standard hydraulic testing parameters, but few details are available, as shown in Section 2.5.

Netzsch Progressive Cavity Pumps Approaching HTL Pressures

The Netzsch progressive cavity pumps appear to be able to approach pressures for HTL slurry feeding applications. This technology was not down-selected in the original pump survey, as previously many of the progressive cavity vendors indicated that the pressure/flow requirements were too high. This is detailed in Section 3.19.

Struvite Management as a Brainstorm for Insoluble Salts Management in HTL

After reading about prevention of struvite formation in waste water treatment plants, it may be worth digging deeper into how HTL can be integrated with better methods to recover inorganic salts (Section 2.4.3).

Identified Potential Recirculation Pump for Laboratory Scale Circulating Bed Retrofit

The Parker magnetically coupled high-pressure, high-temperature recirculation pump is discussed in Section 6.5 and may be a potential replacement acceptable for a refit of a laboratory circulating bed, reaching 5,000 psi and 340°C. Contact with the local vendor representative is underway to assess the application.

Identified Demonstration Scale Catalysis Recirculation Pumps

A series of vendors were identified that provided high-temperature, high-pressure pumps that approach the conditions required for recirculating catalytic upgrading beds is discussed in Section 0.

ABEL High Pressure Plunger Pump Not Identified in Original Survey

The ABEL HP/HPT high pressure plunger pump was not discussed in the original survey. A summary of the capabilities is found in Section 2.1.2; however, it must be determined if this pump is compatible with slurries.

Acronyms and Abbreviations

COTS	commercial off-the-shelf
HT/HP	high-temperature, high-pressure
HTDC	
HTL	hydrothermal liquefaction
PNNL	Pacific Northwest National Laboratory
PWR	Pratt & Whitney Rocketdyne
TEA	technical economic analysis
WWTF	wastewater treatment facility
WWTP	wastewater treatment plant

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1.0 Introduction

1.1 Background

In 2011, Pacific Northwest National Laboratory (PNNL), working as a partner in the National Advanced Biofuels Consortium, issued a report assessing the viable industrial feed system and pump options for a 2000 dry metric tons per day production-scale hydrothermal liquefaction (HTL) plant (Berglin et al. 2012). This report was issued as PNNL-21981, *Review and Assessment of Commercial Vendors/Options for Feeding and Pumping Biomass Slurries for Hydrothermal Liquefaction*, and will be referred to as “Pump Survey” for reference. It had the following scope:

- Identify relevant applications and industries operating at comparable scales
- Interact with commercial vendors and pursue integration between vendors
- Take advantage of commercial off-the-shelf (COTS) technology
- Supply and support vendor needs for biomass feedstock rheology characterization
- Provide vendors with process requirements to support selection of conceptual design for feedstock handing and pump system
- Obtain cost data to the extent possible from equipment vendors to support the technical economic analysis (TEA)
- Identify issues associated scale-up.

The current document represents an update to the prior report in order to:

1. Identify advancements in vendor-reported technologies
2. List reports of new experience or trials with biomass pumping applications
3. Determine if technology/application gaps identified in the prior report have been filled
4. Capture ideas on future research.

1.2 Approach

The methodology for this report was chosen to seek out updates and chase interesting trails primarily using the Pump Survey to triage the search, as opposed to sifting through the vast pumping industry for new leads to follow. Thus, the effort was limited in scope and depth to serve as a check-up over the period from 2011 to 2019.

Additionally, part of the search included identifying high-temperature, high-pressure (HT/HP) recirculation pumps in this field. It was decided to add HT/HP pumps in order to provide a quick survey of the availability and technical maturity of HT/HP pumps that could have utility in recirculating HTL or recirculating post-processing, particularly in the area of pilot scale for the purposes of laboratory research.

The approach covered the period of the original pump survey from 2011 to 2019:

1. Sift through news, updates, and reports from each of the representative vendors in Chapter 2 to:

a. Summarize reports of biomass applications using pump configurations listed in Chapter 3

b. Summarize learning from non-biomass applications from Chapter 3 pump configurations that may have utility in HTL

c. Identify new pump configurations offered by these core companies.

2. Perform limited review of all vendors reported in Pump Survey Appendix E, guided by the "notes" column, to look for indications of biomass slurry interest that has developed since the original update.

3. Identify HT/HP pumps from vendors in Chapter 2, Appendix E, and through standard search engines.

4. Seek opportunity targets to delve into interesting technical "rabbit trails" to consider their potential utility for HTL, as guided by recent experience with HTL.

The original pump survey was used to identify manufacturers to search for relevant updates with respect to HTL. For this update, priority was given to new biomass experience at HTL operating conditions, new relevant reports on pump longevity and durability pumping severe feedstocks, additional pump offerings or technologies, upgraded capabilities, and enabling technologies that may also be useful for biomass HTL.

In the original pump survey, many vendors were identified in the search for viable HTL pump vendors, but only those with the highest potential were selected for detailed assessment. The vendors that were not selected were summarized in Appendix E of the original survey. For this reason, a very brief look was performed at the Appendix E vendors guided by the "notes" column to look for indications of biomass slurry interest that has developed since the original update.

The following sources were used as starting points for this evaluation:

1. Vendor websites for Chapter 2 and Appendix E vendors. Updates were documented as companies have been bought, sold, or become inactive since 2011

2. Electronic trade journals and websites in wastewater treatment and to a limited extent mining, as these areas have related applications

3. Standard search engines for keywords related to high-pressure slurry pumping, HT/HP pumps, etc.

4. Contacts from international research networks, such as IEA Bioenergy Task 34

5. As the period from 2011 to 2019 is large in internet terms, extensive use was made of the internet archive at http://web.archive.org to dig deeper into expired, retired, and redacted updates of webpages from Chapter 2 and Appendix E.

Direct contact with vendors was not performed, with limited exceptions, due to the limited scope and nature of this update.

2.0 Updates on Major Vendors identified in Pump Assessment

The original pump survey was used to identify manufacturers to search for relevant updates with respect to HTL. Priority was given to new biomass experience at HTL operating conditions, new relevant reports on pump longevity and durability pumping severe feedstocks, additional pump offerings or technologies, upgraded capabilities, and enabling technologies that may also be useful for biomass HTL.

This section is focused on major pump manufacturers and technologies from the original pump survey.

2.1 ABEL

ABEL pumps detailed in the original pump survey indicated that there were a number of advantages for hydraulic membrane pumps. There have been some additional updates; however, the information in this section also addresses some potential re-application of ABEL features.

2.1.1 Pulsation Dampeners Versus Deliberate Pulsations

ABEL describes (International Mining 2016) the need for pulsation dampeners on reciprocating piston pumps to avoid "vibrations in piping, excessive acceleration head, and influences on downstream processes." However, the pilot-scale research at Aarhus (Section 3.1) showed that pulsations can be advantageous. According to the original pump survey, the ABEL HMT piston-diaphragm pumps are reported to have "low residual pulsation" due to operation of the three heads out of phase and not due to external pulse dampening. Additionally, the current vendor brochure (ABEL N.D.-b) for the HMQ pump indicates that an "appropriately sized pulsation dampener" is required otherwise it would result in high residual pulsation, specifying an "intelligent membrane/diaphragm pulsation dampener."

However, the role of deliberate pulsations may be a potential area of investigation if the frequency and magnitude can be controlled to provide advantage to HTL. The ABEL site contains an incidental graphic[a] "research into pulsation patterns and the load that they create for the pump" showing evaluation data from an application in the range of 0.8 pulses per second.

Allowing pulsation from the pump could potentially result in an increase in the wear profile of valves and other parts. This is noted at multiple places in the ABEL reports, and is specifically listed as an advantage of the triplex and quintuplex configurations that provide additional means to reduce dampening. However, the experience at high-pressure with abrasive mining slurries may be different than if the slurry were biomass.

[a] ABEL website as of April 2019, https://www.abelpumps.com/en/3-Pump-Solutions/New-pump-developments.php

A potential area to investigate would be determining if it were advantageous to run the pulse dampener controller in a method that would introduce, rather than minimize, some pulsation to improve process conditions as was reported in research at Aarhus. This may also argue towards preference on pump configurations with fewer heads depending on what frequency of pulsation is desired. However, in the original pump report, ABEL was reported to recommend the triplex configuration specifically for the purpose of minimizing pulsations. Thus, there may be elements in their experience base that suggests minimizing to be preferable.

2.1.2 ABEL High Pressure Plunger Pump Not Discussed in Original Survey

The ABEL HPT Series high pressure plunger pump (ABEL 2018) did not appear in the original survey and was not discussed in background notes even though it was available in 2011. It is capable of >3000 psi operation above 50 gpm, but it is unclear if it constitutes a high solids slurry pump as it is referred to as a high pressure cleaning pump suggesting low-solids feed. However, listed pumping media included abrasive media, shear-sensitive and swell-critical fluids, in addition to clean liquids of various types. This, combined with availability of valves including plate, cone, and ball, suggest that it is compatible with some forms of slurry. This may prove an alternate pump configuration if it can be verified as compatible with a biomass type by the vendor; however, it may have been left out of the original survey for this reason.

2.1.3 Longevity Example of ABEL HMQ (Hydraulic Piston Membrane)

ABEL reported in March of 2015 the use of their HMQ hydraulic piston membrane pump for transferring abrasive fly ash slurry over long distances. While only up to 25 bar, application demonstrated transfer of slurry at 65% solids content over 7 km distance at 115 m^3/hr. Four pumps have been running at this application since 2010 (ABEL 2015).

2.2 FELUWA Pumpen

In the original pump survey, FELUWA Pumpen was identified as an example manufacturer of hose-diaphragm pumps that could serve as feed pumps for HTL applications.

2.2.1 New Slurry Pump Test System Available

According to a March 2018 press release, FELUWA has installed a new test rig at their headquarters (FELUWA 2018b).

Figure 1. FELUWA Pumpen new slurry pump test system available for customer feed evaluation. Source: FELUWA Pumpen GmbH

FELUWA reports that the unit consists of their MULTISAFE pump, feed tank and agitator, cooler, and diagnostics to allow for 24-hour testing. The system is rated at 14 m^3/h at 250 bar. The test rig appears to be the triplex arrangement, but it does not appear to show any pre-feeding pumps (such as worm feeder) that may be required for fluids of 5,000 pPas or greater. FELUWA reports that the purpose of the new test rig is to analyze the impact of different kinds of media on typical wear parts, such as valve seats and valve bodies, as well as to evaluate their available materials with respect to hydro-abrasive wear imposed by a customer feedstock.

This is assumed to be a replacement for an older test rig that was reported in March of 2014 in a press release (FELUWA 2014) announcing new gearboxes for the advanced TGK 500/400 series pumps.

2.2.2 Increase in Maximum Pressure for MULTISAFE® Double Hose-Diaphragm Pump

In their double hose-diaphragm brochure (FELUWA 2018a), FELUWA claims a maximum delivery pressure of 350 bar with flow rates up to 1350 m^3/h. This represents an increase in the previously reported maximum pressure of 320 bar, which was captured in the original pump report.

Additionally, the specification in a April 2016 press release (FELUWA 2016), FELUWA appeared to have increased their maximum potential pressure of their MULTISAFE double hose-diaphragm pump as suitable for pressures up to 500 bar but with flow rates up to 1,000 m^3/h. Additionally, the higher pressure of 500 bar was also announced in a press release of January 2017, but that announcement was quietly revised downwards to 350 bar in November 2017 and the original release is only available via internet archives (FELUWA 2017). The April 2016 press release still shows the 500 bar claim, so it is unclear which is accurate.

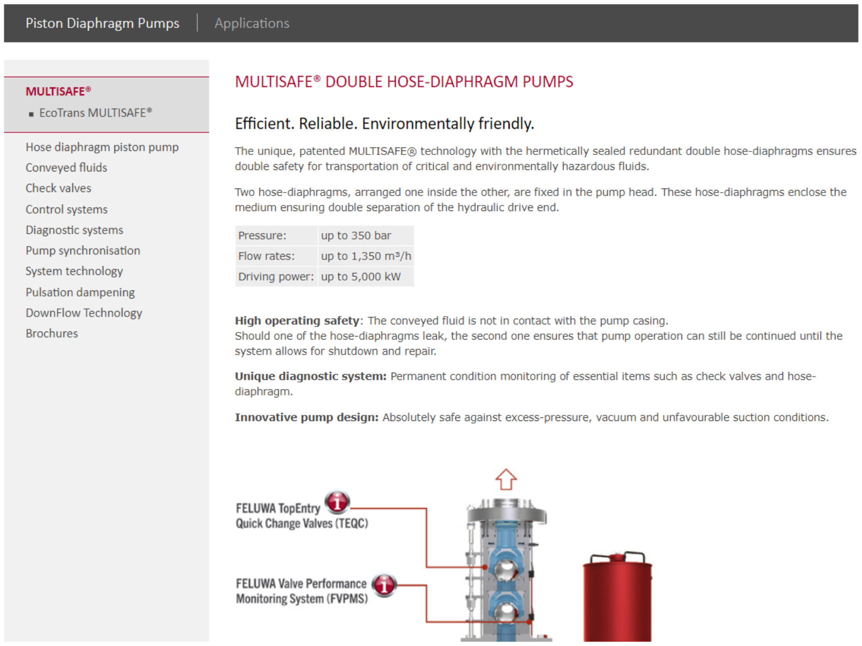

Figure 2. FELUWA Diaphragm pump literature still showing 500 bar maximum pressure. Source: FELUWA Pumpen GmbH

It is unclear if this is represents an attempted improvement or an error. Regardless, most sources suggest that there has been an increase in reported maximum pressures to at least 350 bar and there may be additional improvements pending.

It should be noted that these extended pressure ratings may be important to HTL applications, even for those above the operating requirements for HTL, because the pump pressure threshold to be considered for HTL applications was near the operating pressure of HTL. At a lab scale, there is little difference between the pressure measured in the pump and various unit operations. At larger scale, the geometry of the feeding system may change resulting in faster linear velocities in the feed lines and increases in friction loss, particularly in the colder lines such as between the feed pump and the throat of the preheaters. This is reflected in the vendor news reports in applications transferring abrasive slurries to an atmospheric pressure storage, as the delivery pressure of the specified pumps is in the hundreds of bar as required to overcome heights and friction losses over extended distances.

2.3 Putzmeister

Putzmeister's reported success stories and news focuses primarily on construction applications rather than biomass or similar slurries.[a] No pertinent updates were identified as enabling since the original pump survey.

[a] https://www.putzmeister.com/web/americas/putzmeister-in-the-news

2.4 Schwing Bioset

2.4.1 Improvements to Run Positive Displacement Pumps Without Pulsation

A July 2018 announcement (Brown 2018) indicates that Schwing has redesigned their multi-cylinder positive displacement pumps to provide smooth handoff and avoid pulsations at switchover. This follows on multiple indications that Schwing has been demonstrating proprietary pump control techniques for mitigating pulsations such as in Peru (Jahncke 2016b), a mining application in Mexico (Jahncke 2016a), the Pinos Altos mine in Mexico (Brown and Diaz N.D.), and generic piston pump applications (Brown 2018).

The report from the release included:

> "Continuous flow is attained by operating each hydraulic cylinder of the piston pump independently. While one cylinder is discharging, the opposite cylinder retracts at a faster rate to fill its material cylinder, then begins to move forward to pre-compress the product in the cylinder, such that it matches the system pressure. As the pumping cylinder nears the end of its stroke it begins to ramp down to zero speed.
>
> "The opposite cylinder during this period likewise ramps up its speed such that the total volume being discharged into the pipeline remains constant. Once the first cylinder arrives at a zero speed, it then retracts at an accelerated rate to charge and pre-compress its cylinder, to begin its pumping stroke again once the opposing cylinder begins to decelerate. This achieves a virtually constant flow rate, only limited by the electronic proportional control.
>
> "With this new development, each working cylinder gets a control block to support the required oil flow, independent from the other cylinder. The independently operating hydraulic cylinders are equipped with position transducers which allows their direction, position, and speed to be controlled continuously through a PLC."

While this control approach is not revolutionary (this independent control scheme has been used extensively on Isco syringe pumps), it does indicate that there is continued development and interest in improving products for the high-pressure applications in addition to their main focus on biosolids production at lower pressure.

2.4.2 Schwing Bioset Pipe Lubrication Approach May Have Positive Implications for HTL

The company has promoted a "slip ring" lubrication approach for reducing pumping friction losses, but this approach may improve HTL feed handling in unexpected ways. If this approach is applied to HTL by providing a boundary layer of process water between the feed slug and the walls, it may reduce the potential for overcooking and charring in the heat exchange unit operations of HTL, reduce segregation of biomass in dead spots or retention of heavier/stickier biomass components, and improve heat transfer by using the boundary layer as a transfer fluid, in addition to its original purpose of reducing line friction loss.

2.4.2.1 Background

The information has appeared in a number of company press releases from 2012 on. In a side note on the Southerly Wastewater Treatment Plant in Columbus, OH, announcement in March

2012 (Schwing Bioset 2012), it was indicated that they use a pipeline lubrication system even with high-pressure pumps, particularly when pumping over extended distances. The methodology is described as the water lubricant is injected into a 360° annular groove cut into the inner wall of the tube that puts a thin film of water between the feed slug and the pipe wall. This separates the viscous and sticky feed from the inner wall, and reduces the friction loss such that a 50% reduction in operating pressure is required.

Similarly, an August 2013 article in *Treatment Plant Operator* magazine (Trojak 2012) describing an application for biosolids handling at a wastewater treatment plant (WWTP) in Glens Falls, NY, reported a similar side note on "slip ring" pipe lubrication; this time for handling an abrasive slurry of 25% solids content. Similarly, in this application the thin film of water reduces friction losses in order to lower their required delivery pressure, again reported "by as much as 50%." Details from this application included that the slip rings were running about 20%–30% of their capacity, operating intermittently for 2–3 seconds at a time, and adding no more than 3 gallons per hour to the slurry, reported as "minimal" diluent as no flow rates were given for the slurry. However, as the slurry was fed by two KSP-10 pumps, which pump between 2 to 30 GPM each, this suggests that the amount of lubricant water required to provide the intended benefit represented 0.08% to 1% of the total slurry volume. This approach is common to many of their higher pressure applications such as WWTP cake at 27% solids pumping up to 1000 psi at 8,000 lbs/h (Trojak 2015b, c) and other applications on their page.

2.4.2.2 Application to HTL

The concept of injecting a fluid boundary layer in the piping may be useful for any HTL application in two ways. First, in a way unique to HTL, this boundary layer could act to prevent charring of biomass at the pipe walls or reduce potential dead spots or areas where biomass segregation could occur. This is particularly important in the heat-transfer unit operations as the feed goes through the transition points where solids formation and charring have been noted in some configurations. In addition to preventing wall fouling, a boundary layer of water may also act as a heat transfer fluid to more evenly distribute heat into the feed.

Second, the friction reduction provided by the boundary layer as intended may be useful for some applications where the maximum delivery pressure of a pump is close to the needed HTL pressure in the final HTL reactors with small margin for line friction losses.

The examples noted suggest that the various boundary layer benefits for HTL can presumably be obtained through minimal dilution. As far as a chosen lubricant, while clarified process water may be a first consideration, there may be opportunities to use recycled HTL water and potentially recover some of the organics. Additionally, waste oil such as fats, oils, and greases may be appropriate as an injected thin-film lubricant, which would be more likely to maintain its role in the higher temperature piping downstream of the preheaters prior to the slurry entering the throat of the HTL reactors.

2.4.3 Inorganic Salt Management

A consideration for scaled-up HTL is the description of inorganic salt management problems (Wanstrom 2016a, b) in WWTP for precipitation of magnesium ammonium phosphate, struvite, and struvite precursors. It would be worth investigating struvite management approaches to see if there are related techniques that could manage formation of inorganics in the HTL reactor, separations, and let down operations.

The solutions could include integrating liquid-liquid extraction or other separations unit operations, or designing the pressure/temperature let-down train to create specific conditions that will enable higher quality separation and recovery of the inorganics that do not involve rapid knock-outs that can stress fatigue lines and vessels during commercial application.

2.4.4 Schwing Bioset Biomass-Related Notes

Since the 2011 pumping report, support of biosolids production for WWTPs has been a major focus for Schwing. While these operations typically function below the 3000 psi target for HTL, the list is captured as a starting point for potential learning. Schwing also steadily reports higher pressure experience (but not quite to the HTL target of 3000 psi) in mining and abrasive sludge pumping. At the least, the list of related news reports following the 2011 pump report demonstrates the experience gained from handling these biomass materials, particularly in respect to the check-valves.

On wear evaluation with medium-pressure biomass with lubrication, the March 2012 release (Schwing Bioset 2012) on the Southerly WTP in Columbus, OH, reported successful use of four KSP-45V(HD)L-SFMS pumps to run 20%–25% solids sludge over 400 feet across and 100 feet up with pump exit pressures of 1100 psi. Plant personnel reported that the slip ring lubrication was responsible for improved life of pumping rams, poppet valve discs, and seats, with lifetime of wear-part life around 4000 h in near continuous operation over 6 months.

Note that for this biomass application, the report indicated the use of poppet valves for handling this slurry. There was no more detail available, such as the actuation mechanism, sizing, or shapes, but one can infer that this type of valve was both appropriate and likely contributed to the extended wear resistance.

In long-term wear evaluation, an August 2015 news report was published about the City of Stockton's wastewater treatment facility (WWTF) (DiValentino 2015) operating a pair of Schwing KSP-25 pumps for 25 years for moving dewatered sludge cake, with 129,900 hours on the meter.

The Detroit WWTP (Trojak 2015a) used 2 KSP-110V(HD)L (XL models) for moving dewatered WWTP cake at >20% dry solids up 70 feet and then over 500 feet at a rate of 100 wet ton/h with a maximum operating pressure of 1500 psi at the pump head. The endpoint of the sludge does not require such high pressure, but the pump must operate at high pressure to deliver over the considerable distance. The application is not continuous, operating at 30 h/wk at 150 to 200 gpm.

2.5 Weir Mineral

Since the pump review of 2011, Weir has not reported advancements specific to, or that could be related to, HTL centric applications. Weir continues to offer solutions with piston diaphragm and positive displacement pumps that may be compatible with HTL operating conditions. However, biomass applications (MacDonald 2019; Weir 2019a, c, d) reported since then include primarily low-pressure applications such as feed systems to anaerobic digestion.

Weir did report in March 2019 that their Specialty Pump Test Facility has been updated and is available for pump trials for standard hydraulic testing parameters and includes their high-pressure pumps (Weir 2019b). They do not mention longer-term trials that may include wear analysis in their description.

Of note that could be related to biomass applications, Weir Mineral described experience in enabling smooth, high-pressure transfer of variable consistency of feedstock (International Mining 2015) as well as the usual methods for pulsation dampening (van Rijswick and Vlot 2017). Weir suggests success with variable feedstock was by widening the design criteria for the large variety of operating conditions that would be experienced by the changing feed parameters, and then controlling delivery pressure based on downstream line pressure feedback. As HTL is dependent on consistent residence time and thermal input, this may not be directly applicable. As far as pulsation dampening, it is presumed that the same control scheme could be modified to provide deliberate pulsations of a regulated frequency if this is determined to be advantageous to HTL. The stated applications use piston diaphragm pumps transporting mineral slurries up to 20.6 MPa at 263 m^3/h.

2.6 Zeilfelder Pumpen

Zeilfelder has not released any further updates on biomass specific applications or experience since the original pump survey. While the Zeilfelder T-Rex series pumps were originally specified for biomass applications and covered in the original pump survey, the vendor literature (Zeilfelder Pumpen 2012) on the company website has not been updated since May 2012. This indicates that while there may still be interest in high-pressure biomass applications at Zeilfelder, the lack of public announcements or updates to the vendor literature suggests that there has not been much in the way of advancements in pursuing this application.

Interestingly, there appears to be lower maximum pressure in current vendor literature than that which was reported in the original pump survey. However, as the detailed notes supporting the pump survey go into significant depth on pressure staging multiple rotary lobe pumps to achieve pressures as high as 250 bar, it is presumed that the original survey was based on direct, non-public information from the vendor. In the vendor literature, the website does not indicate that they are offering a model that can exceed 70 bar (Zeilfelder Pumpen 2019a), which is the maximum stated pressure of the KS and KDS Blue series rotary lobe pumps (Zeilfelder Pumpen 2019c) that are rated to 450°C, or the KM Blue series multi-wing lobe pump that is only rated to 250°C and 70 bar (Zeilfelder Pumpen 2019b).

3.0 Brief Updates on Other Vendors from Appendix E of Pump Survey

In the original pump survey, many vendors were identified in the search for viable HTL pump vendors, but only those with the highest potential were selected for detailed assessment. The vendors that were not selected were summarized in Appendix E of the original survey.

For this reason, a very brief look was performed at the Appendix E vendors guided by the "notes" column to look for indications of biomass slurry interest that has developed since the original update.

3.1 Aker Wirth GmbH

Now MHWirth.[a] Focused primarily on mine sludge, no new biomass applications (MHWirth 2019).

3.2 Andritz Inc.

Most pumps are still impeller-based or plug-screw fed, which limits the likelihood of high pressure applications developing. Medium-consistency pumps are at 25 bar[b] and the MP series are up to 100 bar,[c] which appears to be the highest pressure application. No-high pressure biomass news.[d]

3.3 BMA Braunschweigische Maschinenbauanstalt AG

No relevant update.[e]

3.4 Boerger, LLC

No relevant updates,[f] most applications at low pressure.

3.5 ChemGrout

No relevant updates; biological and chemical injection applications were blank.[g] Plunger pump is still limited to 2000 psi and grout applications.[h]

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a https://mhwirth.com/
b https://www.andritz.com/products-en/pumps/pumps/medium-consistency
c https://www.andritz.com/products-en/pumps/pumps/high-pressure
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3.6 Coperion GmbH

Extruder focus; no relevant biomass updates.[a]

3.7 Delta Industries Inc.

Concrete focus; no relevant biomass updates.[b]

3.8 Discflo Corporation

No relevant updates; pump max 1480 psi, biomass is low-pressure applications.[c]

3.9 Inno Engineered Products Pte Ltd

No relevant updates.[d]

3.10 LEWA GmbH

LEWA pressure rating changes: Triplex max 1,200 bar (LEWA 2019a), Diaphragm pump M400 head max 1,200 bar,[e] and high pressure plunger pump type KA-H max 3,500 bar.[f]

A new biofuel application was referenced which suggests a relationship with “BtL” for metering high-pressure/high-temperature biomass for biofuels production (LEWA 2019b). As this acronym was deliberately reported with a lowercase “t” it is likely that this refers to the Dutch company “BtG-BtL Biomass to Liquids BV” in the Netherlands. This company is a leading force in Europe for research, development, and commercialization of biomass pyrolysis resulting in the EMPYRO commercial pyrolysis plant in Hengelo, Netherlands. The group has an active and productive research and development operation seeking to advance technology for liquified biomass production and utilization.

Thus, if the reported application is indeed referring to BtG-BtL, then the target feed may likely be bio-oils for upgrading, rather than a biomass slurry. Even if this is a different bio-fuels producer, then some pumps used by this vendor could align with HTL-type applications, but no specifics are given. While interesting, this page was published in April 2016 and does not appear to have been updated since.[g] This is a development that should be investigated further.

3.11 LF Pumping (Europe) Ltd

Deceased. This company appeared to have gone offline in 2014.[h]

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[a] https://www.coperion.com/en/news-media/newsroom/
[b] https://delta-ind.com/news-press/
[c] https://discflo.com/products/
[d] https://innopumps.com/industries-served/
[e] https://www.lewa.com/en/pumps/process-pumps/lewa-ecoflow-process-diaphragm-pump#position-technicaldata
[f] https://www.lewa.com/en/pumps/process-pumps/lewa-high-pressure-plunger-pumps#position-technicaldata
[g] https://web.archive.org/web/20160405071745/http://www.lewa.com/en/applications/biofuels/
[h] https://web.archive.org/web/20141217144402/http://www.lfpumping.com/

3.12 LobePro Rotary Pumps

No change; pumps still limited to 175 bar.[a]

3.13 Liberty Process Equipment

No updates; pumps still below 1000 psi, blogs have not been updated since 2011.[b]

3.14 LSM Pumps USA

No update; pumps limited to 230 psi.[c]

3.15 Megator Corporation

No update; lobe pump limited to 425 psi, vendor literature last updated in 2013.[d]

3.16 Milton Roy

Update on available options from Milton Roy. This vendor is now offering pumps based on technology and size that may be more compatible with HTL feeding applications. Previously, the original pump survey noted Milton Roy only as a source for metering pumps, but since 2016 has added new pumps to their line-up, with higher maximum flowrates than the original metering pumps.

3.16.1 Milton Roy High Pressure Diaphragm Pumps

In December of 2016, Milton Roy began offering the MegaRoyal diaphragm process pump, which appears to be of the diaphragm membrane pump family (Miltoy Roy 2016).[e]

Table 1. MegaRoyal Model B Diaphragm Process Pump (Miltoy Roy 2016)

Max Discharge Flow	264 gpm (1,000 Lpm)
Max Discharge Pressure	5,800 psi (400 bar)
Temperature	-10°C to 150°C
Applications	Transport hazardous chemicals at high pressure. Slurry fluid transportation: bauxite, coal water slurry, sewage

[a] http://www.lobepro.com/pumps-systems-performance-summary-chart.php
[b] http://www.libertyprocess.com/pump_lines.html
[c] https://www.lsmpumpsusa.com/article_65_Biomass.cfm
[d] http://www.megator.com/rotary-lobe-pump.php
[e] https://www.miltonroy.com/products/process-pumps/megaroyal-diaphragm-process-pump/#models_specifications

The pump is offered in a triplex configuration listed as Model B in literature. Check valves are two in-series ball check valves on either side of the diaphragm cavity. The diaphragms are hydraulically driven using a reciprocating plunger arrangement. The diaphragm is listed as PTFE for the highest pressure application.

This pump provides another option for a membrane diaphragm pump and has the ability to deliver at 5,800 psi, compared to the ABEL unit at 3,600 psi. While both are higher than needed for throat pressure of the HTL reactor, the additional pressure of either pump may be recommended to overcome line friction losses for production-sized plants that may have longer distances between unit operations. Listed applications included sewage in addition to bauxite and coal water slurry, such that biomass compatibility may also be possible.

3.16.2 Milton Roy Poweroyal® Positive-Displacement Reciprocating Pump

Also in December of 2016, Milton Roy began offering a positive displacement reciprocating pump called the Poweroyal (Milton Roy 2015, 2019).

Table 2. Poweroyal Positive-Displacement Reciprocating Pump Milton Roy 2015, 2019)

Max Discharge Flow	264 gpm (1,000 Lpm)
Max Discharge Pressure	10,152 psi (700 bar)
Temperature	-10°C to 150°C
Applications	Oil and gas industry fluids injection, hydrocarbon processing, chemical processing

The pump was designed for high-pressure and large-delivery volume, and is specified to deliver acids, bases, corrosives, viscous liquids, and abrasive fluids. However, while abrasive fluids are specified, it is not referred to in literature as a slurry pump so it is unclear if high solids content biomass may be able to be transferred by this pump.

The high-pressure end of the pump appears to have smaller check valves that may be less tolerant to fibrous or large-diameter biomass particles. Applications listed were oil and gas industry fluids injection, hydrocarbon processing, and chemical processing.

This pump represents an option for a piston-driven positive-displacement pump such that the compatibility of the check valves and fluid handling with biomass can be determined. However, this pump would be unable to withstand the temperatures required for catalytic slurry bed recirculation.

3.17 Murphy & Dickey, Inc.

No relevant update.[a]

[a] https://murphyanddickey.com/

3.18 Neptune

Now part of PSG Dover company.[a] No updates on slurry-compatible pumps; they now offer a peristaltic hose pump (Abaque), but it only achieves max pressure of 217 psi.[b]

3.19 Netzsch Pumps North America, LLC

Noted that Netzsch progressive cavity pumps appear to be able to meet many of the criteria for HTL feeding applications. The technology was not detailed in the pump survey, as the notes in Appendix E indicated that many of the progressive cavity vendors indicated that the pressure/flow requirements were too high.

According to the Netzsch site, the NEMO progressing cavity pumps are designed for feeds containing solids up to 150 mm and can deliver as high as 240 bar (3500 psi) for special applications, up to 200°C, and up to 2200 gpm (Netzsch N.D.), although the max-pressure/max-flow tradeoff is not detailed. In the brochure, it is not clear if multiple stages are required to achieve the full delivery pressure to HTL conditions.

As far as biomass pumping experience, Netzsch reports some applications with progressive cavity pumps but at lower pressure than HTL.

Biomass mash made from silage, plant cuttings, chicken litter, and manure was macerated in one unit operation and then transported using a progressive cavity NEMO B.Max mixing pump with a max capacity of 70 m^3/h and pressure of 48 bar.[c]

Beet pulp containing 10% by volume sand was transported by progressive cavity immersion pump NEMO BT immersible pump with a max capacity of 10 m^3/h and pressure of 24 bar.[d]

It is unclear if there are advantages or disadvantages to it, but it may be worth adding the progressing cavity technology to the potential options for HTL. Conversely, as of the writing of this report, the rotary lobe pumps offered by Netzsch are low pressure.[e]

3.20 PCM (USA Contact)

No update; EcoMoineau™ I Series appears to be available only up to 2900 psi at special request (PCM 2016).

3.21 Pratt & Whitney Rocketdyne (PWR)

As of update in 2018, PWR is still working on their dry solids pump, with torque limited to 150 psi (NETL N.D.; Saunders 2018). They will be aiming for 500 psi. It seems unlikely that this application would be able to reach HTL pressures of 3000 psi.

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[a] https://www.psgdover.com/en/neptune/front
[b] https://www.psgdover.com/en/neptune/test-abaque-family-americas
[c] https://pumps.netzsch.com/us/materials-applications/small-biogas-plants/
[d] https://pumps.netzsch.com/us/materials-applications/biogas-agriculture/
[e] https://pumps.netzsch.com/us/products-accessories/

3.22 Pulsafeeder Engineered Products Operation (EPO)

No update. As in 2012,[a] Pulsafeeder still currently offers a series of hydraulically operated diaphragm pumps[b] of similar maximum pressures, but there is no indication that the manufacturer has expanded the line to manage high-viscosity slurries.

3.23 Roper Pump Company

No update. Pumps still limited in pressure[c] similar to note in Appendix E of original pump survey.

3.24 Saxhund International GmbH

No update. Vendor pumps still limited to 100 bar[d] similar to note in Appendix E of pump survey.

3.25 Seepex GmbH

No update. Vendor pumps do not reach HTL requirement[e] similar to note in Appendix E of survey.

3.26 Stamet Inc.

Not found.

3.27 Sultzer Pumps (US) Inc.

No update. Progressing cavity pumps do not reach HTL pressure[f]; multiphase pumps are not listed as compatible with biomass type slurries.[g]

3.28 TK Energi A/S

Webpage defunct as of 2016.[h]

3.29 Verder Inc.

No update; pump lines do not appear to reach HTL conditions.[i]

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[a] http://www.pulsa.com/technologies/hydraulically-actuated-diaphragm-pumps.asp
[b] http://pulsa.com/hydraulic-diaphragm-pumps/
[c] https://www.roperpumps.com/gear-pumps
[d] http://www.saxlund.de/en/produkte/feststoffpumpe/
[e] https://www.seepex.com/us/pumps-and-control-systems/?no_cache=1
[f] https://www.sulzer.com/en/products/pumps/pumps-by-type/progressing-cavity-pumps
[g] https://www.sulzer.com/en/shared/products/2017/04/19/13/40/multiphase-pump
[h] https://web.archive.org/web/20160111092810/http://tke.dk/#/
[i] https://www.verderliquids.com/int/en/purchasing-progessing-cavity-pumps-verderpro/vpr-feed-hopper-pump/

3.30 Vogelsang

No update; pumps do not appear to reach HTL conditions.[a]

3.31 Wangen Pumps

No update; progressing cavity pumps do not meet HTL pressure conditions.[b]

3.32 Wastecorp Pumps

No update; pumps do not appear to match HTL conditions.[c]

3.33 Wright Flow Technologies

No update, rotary lobe pumps do not appear to match HTL pressure conditions.[d]

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[a] https://www.vogelsang.info/en-in/products/pumps/
[b] http://www.wangen.com/en/products/technology/
[c] https://wastecorp.com/Products
[d] http://www.wrightflowtechnologies.com/products/rotarylobe/index.asp

4.0 Newly Identified Companies

Engineering Dobersek was identified as a German provider of industrial piston diaphragm pumps as part of turn-key systems. As they are a solution provider, there are not specifications around the pumps used, and it is likely that they may be obtained from a dedicated pump manufacturer. The site lists pumping specifications as “above 100 bar” and up to 5000 m^3/h. Reference projects are primarily in Eastern Europe, Russia, and former Soviet states.

5.0 Other Considerations and Research Applications

5.1 Liquid Oscillation During HTL at Aarhus University

HTL researchers at Aarhus University described subjecting the feed to deliberate pulsations through the preheating zones to increase turbulence for the purpose of increased mixing and improved heat transfer (Anastasakis et al. 2018). The concept leans on using a separate pump or device to deliberately retract and advance the process liquid throughout the HTL process as described in a related patent (Johannsen et al. 2016). Note that because the patent is limited to supercritical conditions, it will likely not inhibit use of the concept in near-critical HTL as it is currently envisioned. Note also that the concept may not merit the cost of adding unit operations to support oscillation, as the same effect may be obtained by synchronizing multiple pump heads with pulsation control software at the demonstration or commercial scale. This could be accomplished by retuning the pulsation dampening software used to synchronize multi-head pumps by some of the vendors in this report, to instead simulate a very low frequency pulsation, although it would not provide an actual retract stroke.

The concept involves using a pair of pistons at either end of the HTL system that alternately fill and discharge to retract or advance the process fluid in all lines and unit operations in between as shown in Figure 3.

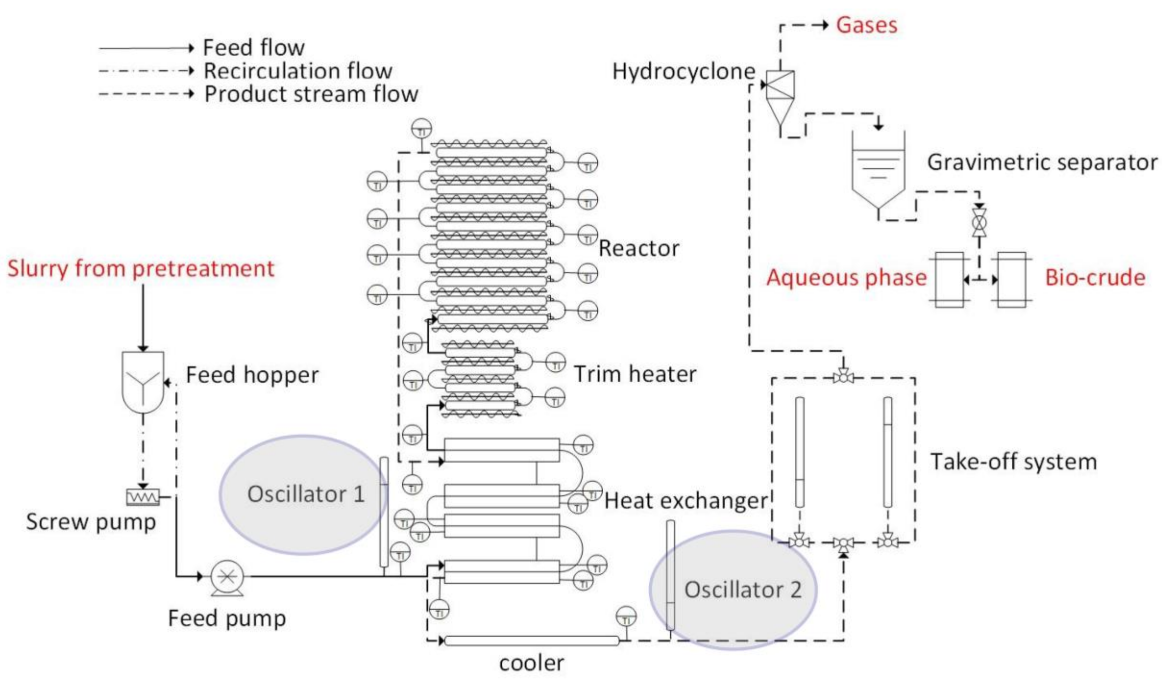

Figure 3. Aarhus continuous HTL system with liquid oscillation (circled) (Anastasakis et al. 2018).

Engaging the oscillators causes the liquid flow in between to retract and advance in the lines. There is a small, observable impact from engaging and disengaging oscillation on the heat profile of the heat exchanger and reactor as shown in Figure 4.

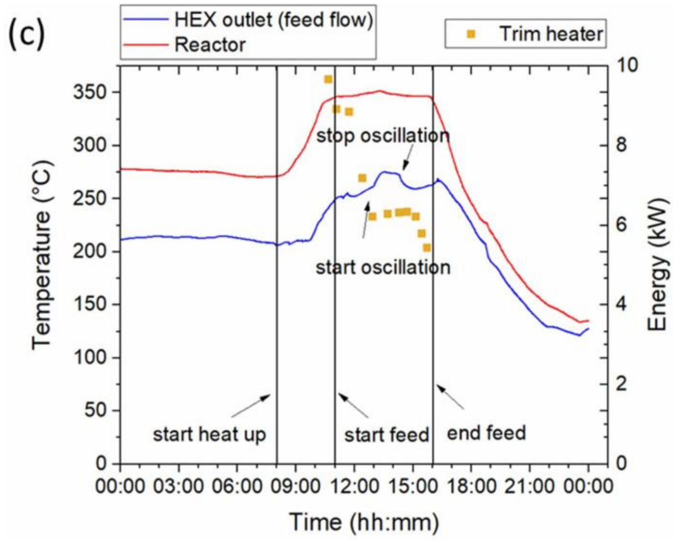

Figure 4. Aarhus continuous HTL heat exchanger (HEX) and reactor temperatures with and without oscillation (Anastasakis et al. 2018).

As far as the magnitude of impact, the researchers noted a positive impact in heat recovery and transfer, but could not yet identify an impact on the HTL yield or conversion impacts that would support any benefits of enhanced mixing.

However, it is likely that there may be some benefit to mixing, which could also include preventing separation of solids in the lines that could lead to accumulation, carbonization, and/or overcooking of the biomass in the heat transfer and reactor units.

The frequency used for oscillation in the Aarhus research is not disclosed in the 2018 paper, but it is likely between 2 to 3 cycles per minute. This was based on the nominal experimental flowrate of 1 lph and the swept volume of the oscillators being 0.5 liter each. Thus, the minimum frequency would be 1/min, which is the frequency required to alternately stall flow and provide twice the flow. The frequency of 2 to 4 cycles per minute would be a likely research approach.

A potential disadvantage of this is the possibility to cause pressure cycle stress on the piping and unit operations, which is a principal concern raised by some of the pump manufacturers in this survey. It may be possible to provide a gentle pulsation ramp through the use of pulsation control software on multi-headed pumps at the demonstration or commercial scale. However, this approach would not produce an actual retract stroke where the liquid is travelling backwards in the system, but changes in the linear velocity of the process liquid may achieve much of the same benefit.

For this reason, research from Aarhus in this area should be monitored, as well as determining if this approach can be tested at the research scale.

5.2 Pilot-Scale Biomass Slurry Pump, Aerodyne Research and Worcester Polytechnic

In 2013, Aerodyne Research in cooperation with Worchester Polytechnic Institute was awarded a Small Business Technology Transfer grant from the U.S. Department of Energy for the purposes of developing a biomass slurry pump at pilot scale (US DOE 2013). The approach was centered on enabling hydrothermal liquefaction by developing the pump to flow at low and medium rates for pilot-scale HTL, and references the original PNNL pump survey as a starting point to establish the needed requirements for a pilot-scale pump application (Aerodyne 2014).

As a summary, the output of the study was to propose a large syringe-type pump with recirculation of the syringe cavity, conceptually similar to known laboratory syringe pumps but larger and with internal recirculation. It was not reported if other pump concepts were considered as part of this effort.

The effort had three primary tasks—a settling study of biomass slurry, a paper-study of potential check valve types, and testing the HTL process using a 10% solids slurry, fed with a prototype single cylinder syringe. The prototype pump did not appear to have check valves nor the ability to provide continuous flow. The HTL task included analytical and experimental results as part of this.

The effort suggests the reality that, for the time being, the syringe-type pump that is often used at research scale may be a reasonable approach for pilot scale biomass HTL, as this there were not significant findings to the contrary in this work. Particularly, in the authors' experience, the limitations imposed on syringe pumps at the research scale can be addressed by short stroking a syringe pump or using smaller syringes to avoid in-pump biomass slurry settling, using large bore check valves to address biomass particle size, and pressure-feeding syringe pumps during refill to address biomass slurry flowability.

6.0 High-Temperature, High-Pressure Recirculation Pumps for Bio-crude Catalysis

Continuously recycled reactors, such as ebullated beds, have been considered for downstream catalysis of HTL oils to subsequent products. For this reason, a survey of hot-fluid, high-pressure recycle pumps was performed to catalog the potential options for a recycle pump that could operate at the conditions required for catalytic conversion. Typically, these systems operate with a maximum pressure of 2000 psi (138 bar) and a maximum temperature of 450°C. However, the fluid is less challenging, as the recycled mobile phase may be raw or hydrotreated bio-crudes, which will be low in solids content, and when recirculated at reaction temperature required for catalytic upgrading, lower viscosity than HTL feed.

As far as a slurry bed reactor, there are multiple approaches to agitation and/or recirculation. For the purposes of this discussion, process pumps will be evaluated with respect to using a pump to provide liquid recirculation of the mobile phase; this requires the pump to continuously withstand catalytic upgrading reaction conditions. However, for this assessment, while the process will be as high as 2000 psi, it will be assumed that the recirculation stream is returning to the vessel with less than 50 psi differential pressure between the inlet and outlet.

Furthermore, catalyst retention will be assumed for a potential recirculation application such that the recirculating fluid will not be a slurry, but may contain a small amount of catalyst fines. Lastly, some considerations will be given to the potential impact to a given pump if partially reacted bio-crudes are present in the recirculating fluid due to reactor shortcutting that can occur in continuously stirred tank reactors.

6.1 Zeilfelder Pumpen

6.1.1 Zeilfelder Rotary Lobe Pump

This positive displacement pump is well suited to the temperature and pressure requirements for both feeding and recirculating bio-crudes and mobile phases of various catalytic upgrading reactors for HTL products. They appear to also be designed for solids and abrasive feeds, which would not be needed in a catalytic upgrading application. Notably, they also offer explosion-proof and seal-less pumps for the petrochemical industry, which may be more compatible with catalytic reactor recirculation due to the hydrogen and hydrocarbon mobile phase and product.

Zeilfelder was included in the original pump survey as a potential source for rotary lobe pumps (Zeilfelder Pumpen 2019d) for HTL feeding, and was described at length. In summary of the original survey, the rotary lobe pump is a category of positive displacement pumps where the mobile phase is pumped around the interior of the pump casing in the lobe cavity—they are gear-driven, they do not require valves, and the lobes do not make physical contact. This qualifies them for high-viscosity fluid pumping with or without solids.

While some of the pumps are rated to 450°C, it was noted previously that there was a difference in the Zeilfelder vendor literature that the stated pressure maximum was 120 bar (Zeilfelder Pumpen 2019a) compared to 250 bar in the original pump survey. However, regardless of the outcome, 120 bar (1760 psi) represents a sufficient pressure for successful catalytic upgrading of HTL oil.

Additionally, for use in a catalytic circulating reactor, the previously identified disadvantage of this pump for HTL feed applications (the need for multi-pump staging in 50-bar increments) is not applicable for use as catalytic recirculation. The use of the pumps as a catalytic feed pump would also require fewer stages to achieve 120 to 150 bar.

Table 3. Zeilfelder lobe pump specifications

	KE & KD Blue	KS & KDS Blue (Zeilfelder Pumpen 2019c)	KM Blue (multi-wing) (Zeilfelder Pumpen 2019b)
Press (bar)	Up to 40	Up to 70	Up to 70
Viscosity max	3,400,000 mPas	3,400,000 mPas	3,400,000 mPas
Flow rate	1 to 5,000 lpm	2 to 2,474 lpm	2 to 3,875 lpm
Temperature	Up to 450°C	Up to 450°C	Up to 250°C
Min. volume hydrotreater it can feed	430 liter	430 liter	430 liter
Min. volume CSTR it can recirc	1.8 liter	1.8 liter	Not high enough T

The use of this rotary lobe pump may not have utility as a primary feed pump for pilot and smaller applications, because the pump as sold has too high of a flowrate. However, the example pump may be appropriate for catalytic recirculation, which is sized larger to achieve faster internal recirculation relative to the smaller volume of biomass that would be fed to a pilot-scale system.

As a quick calculation, the smallest size single-pass catalytic reactor that could be fed with the smallest KD/KE Blue Size 15 would be approximately 430 liter hydrotreater, which is significantly larger than what would be considered for a pilot-scale upgrading reactor. This is based on the KD/KE Blue 15 minimum flowrate of 1.8 lpm feeding a typical hydrotreater at 0.25/hr. weight hourly space velocity.

In comparison, the same pump could be used for a pilot-scale recirculating reactor. As a quick scale estimate, for a circulating stirred tank reactor or an ebullated bed this may be appropriately sized for as small as an 1800 ml reactor, assuming 1 turnover per minute. This is approximately 3 to 4 times the size of the catalyst bed inside of the pilot-scale ebullated bed reactor used by the authors, and will be considered as a potential upgrade to that system.

6.1.2 Zeilfelder External Gear Pumps

The external gear pumps are also well suited to the temperature and pressure requirements for feeding or recirculating bio-crudes and hot mobile phases for catalytic upgrading (Zeilfelder Pumpen 2019a). The close tolerance of the gears suggests that they are not tolerant to solids, which is not an issue for this application. There are also explosion-proof and seal-less pump options available, which may be needed with catalytic upgrading of HTL oils.

Table 4. Zeilfelder gear pump specifications (Zeilfelder Pumpen 2019a).

	ZK Blue	ZH/ZV Blue
Press, max (bar)	120	120
Viscosity, max	150,000 mPas	150,000 mPas

Flow rate, range	0.4 to 300 lpm	1 to 4,350 lpm
Temp, max	450°C	450°C
Min. volume hydrotreater it can feed	100 liter	250 liter
Min. volume CSTR it can recirc	0.4 liter	1 liter

As far as use as a feed pump for pilot and smaller applications, the gear pump may not be usable for feeding pilot or smaller systems, but it may be useful for a catalytic recirculation. The smallest size catalytic reactor that could be fed with the small ZK Blue Size 2 would be approximately 100 liter hydrotreater, which is 5 times the size of HTDC. This is based on the ZK Blue 2 minimum flowrate of 0.4 lpm feeding a typical hydrotreater at 0.25/hr. WHSV.

However, for a circulating stirred tank reactor or an ebullated bed, this may be appropriately sized for a 400 ml or larger bed assuming 1 turnover per minute, which is slightly less than the catalytic bed in the ebullated bed reactor used by the authors.

The Zeilfelder-offered internal gear pumps may not be appropriate due to only being able to withstand 14 bar and 300°C (Zeilfelder Pumpen 2019e).

6.2 Flowserve

Flowserve markets a variety of hydrocarbon pumps. The PR Reactor Recycle (Ebullating) and Recirculation Boosting Systems is an example of a pump that would be well suited for use in a high-temperature recirculation catalytic upgrading of HTL oils. The pump operates at reaction conditions, up to 210 bar, 480°C, and a hydrocarbon and hydrogen-rich environment (Flowserve 2012a).

The unit is often used as an ebullated bed recirculation system, which approximates the conditions that would be required to perform recirculated heavy phase upgrading of bio-crudes at relatively similar temperature and pressure. A primary example application is the ebullated bed catalytic hydrocrackers for upgrading of heavy oils, vacuum gas oils and residues, and coal slurries. In this case, the recirculated oils are lower in solids content, as well as at lower viscosity due to the temperature. Another example application for the PR pump from Flowserve is for distillate hydrocracking processes in order to boost pressure between reactor vessels. A further example is the 2012 application of the PR series pumps for the DuPont IsoTherming process used to recycle hot mobile phase back into a hydrocracking reactor for improving product yield from petroleum.

The original ebullated bed pump was installed by Flowserve Corporation in 1965 in a Middle Eastern refinery and is still in operation after 50 years. Currently, the manufacturer indicated that there are more than 60 units in active service worldwide (Robbins 2011).

Due to the complexity of ebullated bed applications, Flowserve has also designed monitoring and diagnostic utilities for managing and predicting developing problems within a given processing environment (Flowserve 2012b). Considering the complexity of biomass upgrading, this mature monitoring approach is likely to be a critical need for reliable upgrading.

There is not significant additional technical detail available online from Flowserve, and there does not appear to be many other manufacturers of similar ebullated bed pumps. Further application details will be needed to be obtained in subsequent conversations with Flowserve.

6.3 Example of Canned Pump Motor Application (Chempump)

The canned motor centrifugal pump is a form of seal-less pump sometimes referred to as a hermetically sealed pump. It is designed such that the pump head and the drive shaft and motor are exposed to the process fluid. This is a response to applications that could experience leakage when a traditional pump is used that has a seal between the drive head and the drive motor, particularly for more extreme applications including high-temperature, high-pressure, chemical incompatibility, mechanical wear by moving parts on the seals, or other environments.

In Figure 5, the process fluid in yellow is shown circulating through the pump housing and drive shaft and acting as the primary lubricant for the pump. This is an interesting analog of the magnetically coupled pump, except in this case the magnetic coupling is the motor itself, rather than on the drive shaft. Thus, for the canned motor the pressure boundary exists between the rotor and the stator, rather than between the impeller chamber and the drive shaft.

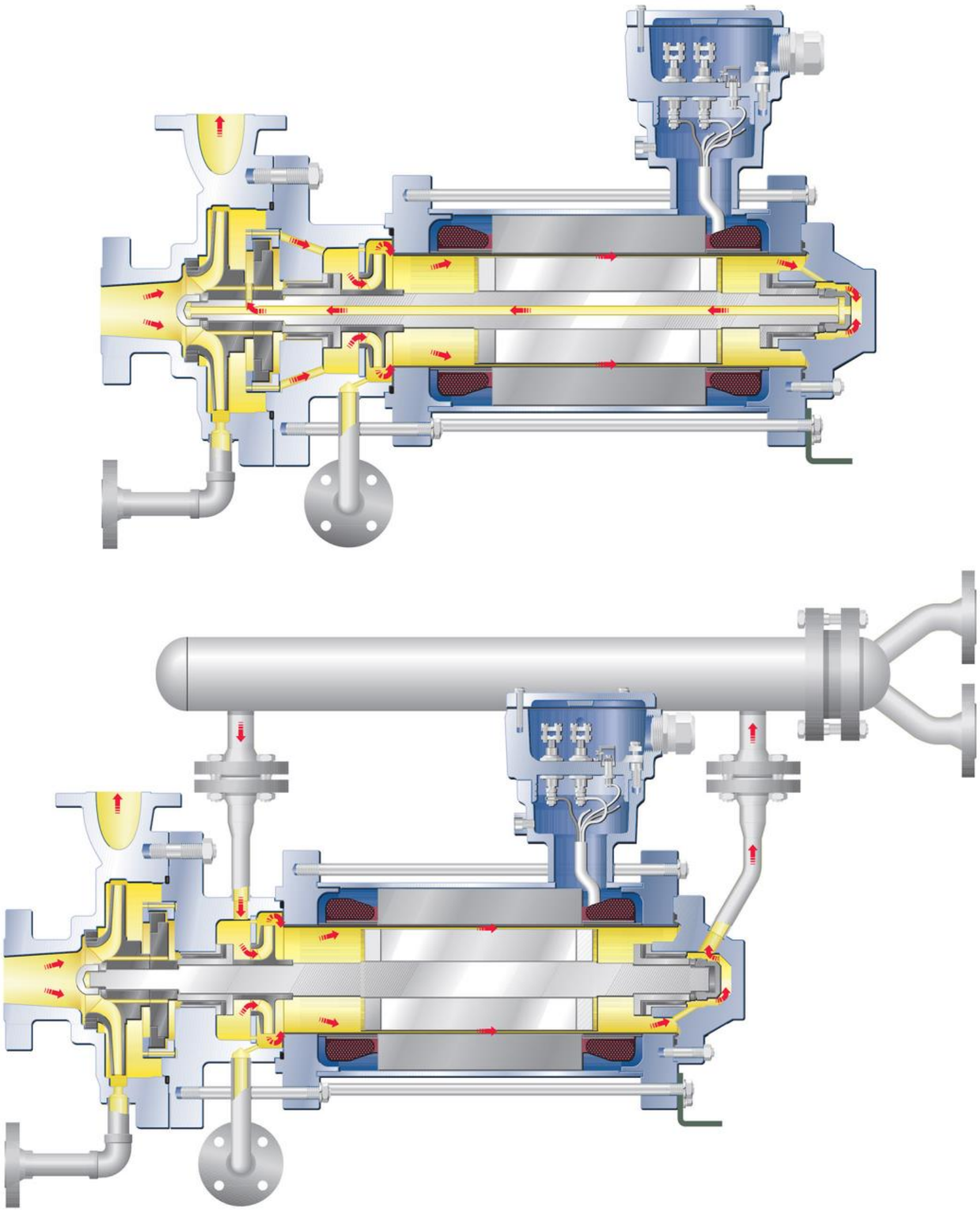

Figure 5. Canned motor pump cross section (reproduced with permission from HERMETIC-Pumps, Inc., Houston, TX)

As such, companies such as Teikoku offer the Chempump Class C, which can achieve as high as 400°C, and the Class R oil-filled "T" model, which can be exposed to 540°C, and theoretically up to 5000 psi (Chempump 2010) during recirculation. Note that this is for a recirculation application, as a feeding application would likely require a large number of stages to achieve high pressure.

This configuration has advantages that come with sealed impeller pumps, but potentially include the ability to apply higher torque to the impeller than a magnetically coupled pump. As far as maintenance durability this pump rates well. It has been reported that for refinery use the canned motor pump has been demonstrating a mean time between repairs of 7.5 years (Chempump 2010).

A potential disadvantage is the compatibility of partly upgraded bio-oil in the pump housing. While modifications can allow these pumps to mitigate the presence of solids in the target fluid, there are limitations in the mechanical function that have the potential to impede its use as a recirculation pump for catalytic bio-crude upgrading (Jaskiewicz 1991). The lubrication channels represent a potential incompatibility with partially upgraded HTL bio-crudes. Particularly any dead spots in the flow path as well as the bearing races may be susceptible to accumulation of long chain hydrocarbons or tars that could reduce lubrication of the moving parts. As the pump is maintained at high temperature, there is also an outside possibility that tars sequestered in dead spots could slowly react to form longer chain gels and solids that would interfere with mechanical operation.

6.4 Klaus Union, Magnetic Drive Pump

The magnetic drive pump is another type of centrifugal, seal-less pump where the drive motor is separated from the impeller. In this variant, the power from the motor is used to drive a magnetic coupling that imparts force on the impeller.

Shown in Figure 6 as an example version of the magnetic drive pump, the process fluid is shown in blue. Notably, as the process fluid remains in contact with the application side of the magnetic drive coupler, there still remains the potential for process dead-spots and tar sequestration zones inside the drive assembly of the pump. Thus, in this particular application, there is a reduced difference between the magnetic drive pump and the canned motor pump. Comparing Figure 5 to Figure 6, the mechanical components of a canned motor pump are physically similar to those of this magnetic drive pump application.

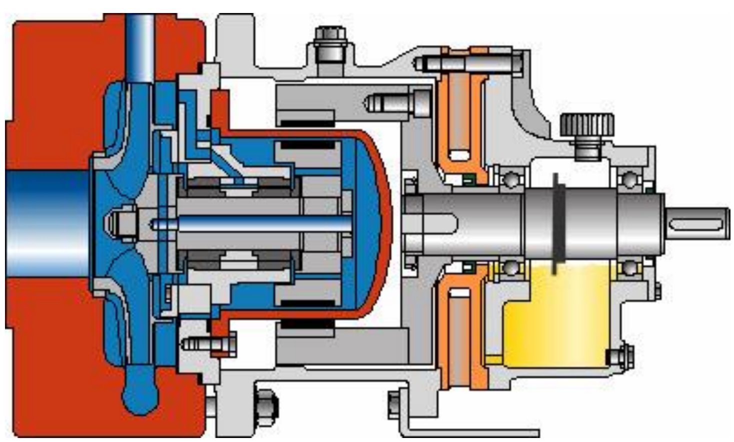

Figure 6. Cutaway of Klaus Union magnetic drive pump SLM-NVH (Klaus Union 2019a; used with permission from Klaus Union).

A similarity between the two pumps is that both impellers of the magnetic and canned pumps are lubricated by process fluid. A difference is that the motor of the magnetic drive pump is lubricated by its own oil instead of process fluid as the canned motor pump is. Furthermore, the magnetic drive has permanent magnets, while the canned pump uses electromagnets on the drive side.

The magnetic drive pump has some advantages. For the magnetic drive, there is a potential for larger thermal gap between the process and the pump motor, and the motor is separated from process fluids. At the same time, approximately 15% of the drive energy is lost through eddy current losses and friction losses through the drive mechanism when compared to the canned motor pump (Bungartz and Bungartz 2016).

For the Klaus Union SLM-NVH pump, the pump has a maximum flowrate of 3500 gpm, maximum pressure of 5,800 psi, and maximum temperature of 400°C. The lower boundary of flow appears to be approximately 6 gpm (Klaus Union 2019b). The manufacturer has a number of different magnetic drive pumps, but this appears to be the only one rated to achieve both the temperature and pressure of catalytic upgrading.

6.5 Parker MagnePump, Magnetically Coupled Pump (Lab Scale)

Parker offers a smaller variant of the magnetically coupled pump that is conceptually similar to the larger-scale units in Section 6.4. This model is available with 0.75 and 1.5 HP motors and is considered a recirculation pump nearly suitable for recycle of catalytic upgrading of bio-crude.[a,b] 5 HP and 7.5 HP variants are available.

The maximum operating temperature is only 343°C, while the maximum working temperature is 5,000 psi for the 0.75 HP and 1.5 HP versions; up to 4,400 psi is optionally available using the 5 and 7.5 HP versions. The maximum flowrate is 72 liters per minute, such that the expected turndown should put it into the range that would be needed for recirculation of a 0.5 liter circulating bed.

Contact was made with the local Parker representative to provide specifications for a research-scale recirculation pump on a stirred tank reactor bed for bio-crude upgrading application. Further details are not yet available.

6.6 Warrender, Mag Drive Centerline Centrifugal Pump

Warrender also offers a magnetic drive pump referred to as the WMCA-API-685 (Warrender Ltd. 2014). This pump claims models with flows between 0.1 and 4500 gpm, a maximum operating temperature of 450°C, and maximum pressures indicated above 1500 psi ("higher pressures available"). The vendor data describes that pressures as high as 2200 psi can be achieved using single or dual Hastelloy C276 or Titanium rear casings. In addition, the lead description on the Warrender site suggests as high as 7250 psi maximum allowable working pressure,[c] but no detail on this variant is given in the brochure.

[a] http://www.autoclaveengineers.com/products/high_pressure_pumps/toc_Magnepumps.html

[b] http://www.autoclaveengineers.com/products/high_pressure_pumps/HPP_MagnePumps_34_15/index.html

[c] http://www.warrender.com/wmca-api-685-centrifugal-mag-drive-pumps.html

6.7 Other Manufacturers Checked But Did Not Meet Pressure/Temperature Criteria for Catalytic Recirculation

The following manufacturers were briefly checked and do not appear to offer pumps that achieve both the pressure of 2000 psi and temperature of 400°C: ABEL,[(a)] Feluwa,[(b)] Schwing Bioset,[(c)] Weir Minerals,[(d)] Goulds Pumps,[(e)] Giant,[(f)] Cat Pumps,[(g)] Blackmer,[(h)] Corken,[(i)] KSB,[(j)] Lawrence Pumps,[(k)] TRUFLO,[(l)] Magnatex,[(m)] OSNA,[(n)] Teikoku (Type BM)_ENREF_30_ENREF_32,[(o)] Sanwa,[(p)] Tuthill,[(q)] Viking,[(r)] Sethco,[(s)] Crane Engineering,[(t)] Liquiflo,[(u)] and Hydrodyne.[(v)]

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a https://www.abelpumps.com/en/index.php
b https://www.feluwa.com/
c http://www.schwingbioset.com/
d https://www.global.weir/industries/mining/
e https://www.gouldspumps.com/en-US/Home/
f https://www.giantpumps.com/
g http://www.catpumps.com/
h https://www.psgdover.com/blackmer
i https://www.corken.com/Home
j https://www.ksb.com/ksb-en/
k https://www.flowserve.com/en/products/all-products?product_brand=561
l https://www.truflo.com/
m https://magnatexpumps.com/
n https://www.osna.de/en/
o http://www.teikokudenki.co.jp/english/products/pump/canned04.html
p http://sanwapump.com/
q https://www.tuthill.com/
r https://www.vikingpump.com/
s http://www.mp-gps.com/brands/sethco
t https://www.craneengineering.net/products/pumps
u http://www.liquiflo.com/v2/
v http://hydrodynepumps.com/high-temperature-pumps.html

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