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Anaerobic Membrane Bioreactors as a Treatment for Wastewater and Biogas Production at University of Massachusetts Amherst

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Introduction

The University of Massachusetts Amherst has its eyes set on a futuristic vision. The goal of revolutionizing campus to an all time level of sustainability is no simple one. Achieving net zero carbon emissions by the year 2032 would require an unprecedented scale of renovation over the given span of time; however we stand before an opportunity to set a regional and nationwide standard in college campus sustainability [8]. The UMass Carbon Mitigation Plan (CMP) outlines a wide array of solutions to be implemented to achieve its goal, that having a clear focus on the campuses lacking heating and cooling efficiency.

The UMass Central Heating Plant (CHP) is the focus of this section of the renovation project. A massive heating plant that centralizes the production and distribution of heat across the 1,400+ acre campus consumes a copious amount of natural resources, primarily non renewable energy sources such as natural gas [8]. The CHP is in desperate need of innovation and renovation as it holds a majority stake in the campus' net carbon emissions.

A viable solution to boosting the CHPs efficiency while mitigating its harmful environmental impact revolves around the implementation of a low temperature hot water system (LTHW). LTHW systems utilize heat from hot water rather than steam, which the CHP currently uses. Distributed hot water with a temperature of roughly 49 to 60 degrees Celsius requires a significantly lower amount of energy to be heated compared to steam [8]. As a retrofit, using hot water would save significant amounts of energy and mitigate reliance on non renewable energy sources, but using more hot water implies that we use more water.

LTHW uses a significantly greater amount of water compared to steam, but another solution could decrease water consumption [5]. By recycling greywater (a non potable water supply reclaimed from municipal use) we can supply that level of demanded water to drive the LTHW distribution. To accomplish this, greywater must be filtered for human health and safety as well as the longevity of the LTHW system itself. Suspended solids and pathogens in the water supply could be detrimental to our health and could degrade the mechanical integrity of the system over time [5]. As a result, it is necessary to incorporate a filtration system such as an anaerobic membrane bioreactor (AnMBR). AnMBR utilizes a permeable membrane lined with a culture of anaerobic bacteria that can consume suspended solids and other unwanted contaminants in the water [3]. By augmenting the LTHW system to utilize a recycled water supply, the CHP will be equipped with a soundly efficient heat distribution system.

Problem Explanation

LTHW and other supporting technologies open up the door to moving away from natural-gas combustion and towards renewable methods for temperature of the UMass Amherst campus. But there are still several questions that must be answered. One of the most vital being, does LTHW use more water than steam? In this chapter, our team explores why this is an important and non-trivial question to answer.

Foremost, steam is used as the heat carrier at UMass. The proposed switch from steam to liquid water as the heat carrier may increase the water consumption needs of campus. The heat transfer between two objects is ultimately controlled by the difference in their respective temperatures, and steam (100 degrees Celsius) and comfortable room temperature (around 22 degrees Celsius) have a much greater difference in temperature that between LTHW (65 C) and comfortable room temperature, steam must be circulated through radiators fewer times to evolve the same amount of heat as hot water would. Assuming steam is circulated at around 112 degrees Celsius and the room being heated is around 25 degrees Celsius, the radiators with steam require less surface area than a LTHW radiator with an estimated temperature of 65 degrees Celsius. The increase in surface area may account for an increase in water mass circulated throughout the system, which is part of this solution that must be studied.

Another area for concern is the adjusted makeup water in either system. Research from a Cold Regions Research & Engineering Laboratory (CRREL) report indicates that nearly 50% of steam produced is not required for heating (and is wasted as such) [1]. This could potentially be due to condensate forming, leaks in the steam pipes, or that fact that steam contains much more heat than the surrounding environment requires in order to feel comfortable. Comfortable temperatures lie around 100 degrees Celsius less than the temperature of steam. Assuming there are leaks in the steam pipes or condensate forms as heat is evolved from radiators, this condensate must be added to the system to account for the lost matter [1]. The question that arises is whether a LTHW system requires more makeup water, due to its liquid nature, than compared to the current adjusted makeup water related to steam heat distribution.

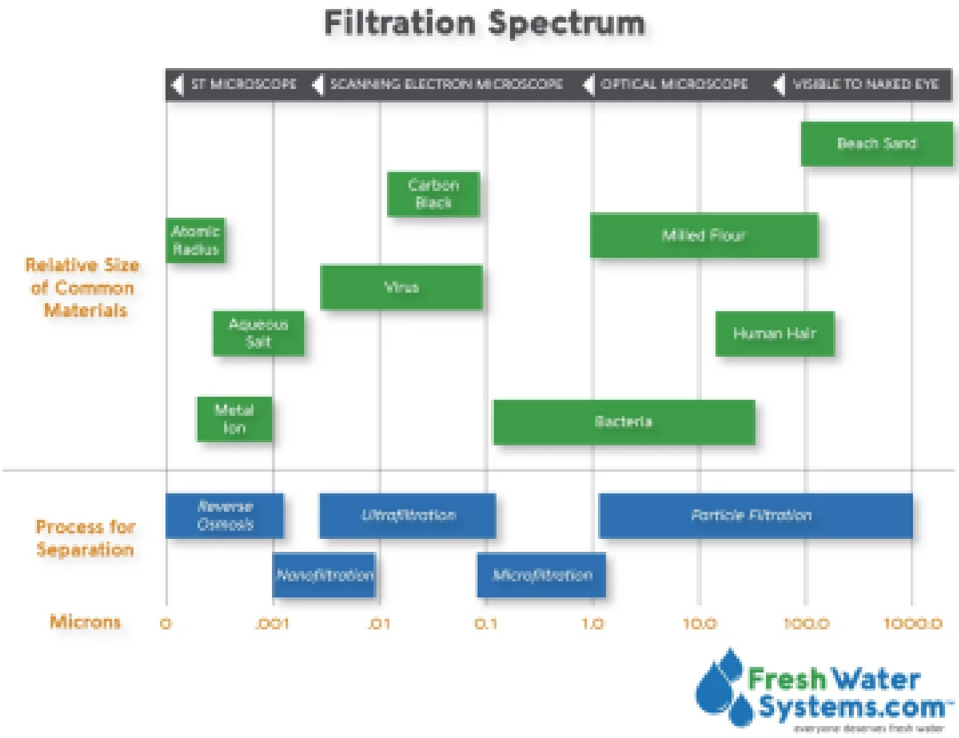
These two components (the initial change in the volume of circulated water as well as the uncertainty of adjusted makeup water between the two systems) are the core problems that must be understood before implementing this proposed LTHW at UMass. These fluctuations in water consumption are directly related to the university's scope three carbon emissions. According to a River Network Report, annually in the U.S. commercial and institutional water-related carbon emissions are responsible for more than 35 million metric tons of CO_2 [2]. Currently, the CHP produces 1.2 billion metric tons of steam per year, at a rate of 356,250 lbs/hr [3]. This is equivalent to roughly 594,000 lbs/hr, if UMass switches to hot water as the heat carrier (assuming the CHP does not increase in efficiency or capacity). Changes in the rate at which water is circulated could, therefore, have an effect on the water usage of UMass and thus carbon emissions as well.

In conclusion, UMass must determine how the transition to LTHW will impact water consumption. UMass must quantify how any increased water consumption will relate to carbon emissions to ensure we are truly approaching a net-zero carbon campus.

Solution Explanation

In order to have an AnMBR, a membrane is required. The membrane facilitates the physical filtration process, so it is crucial to have an adequate membrane. The pores of a polymer membrane are 0.01 - 0.1 microns in diameter, qualifying as ultrafiltration, and can be seen compared to other filtration methods in the filtration spectrum diagram in figure 1 [9]. Ultrafiltration is miniscule enough to completely or significantly reduce bacteria, benzene chlorine, crypto, pesticides, rust, viruses, and odor, and partially reduce algae, chloride, copper, lead, and mercury, while at the same time preserving essential mineral content in the water [9]. Ultrafiltration also operates at a low pressure, putting less stress on the piping. This ensures the human health safety of the system as well as preservation of the longevity of the system.

Figure 1: Filtration spectrum depicting separation capabilities in reference to other filtration systems and



their respective sizes.

The material of the membrane is another vital consideration to the construction of AnMBR. Ceramic, metallic, and polymer membranes are all available, with ceramic and metallic being used for more specialized applications. Ceramic membranes are generally used for exceptionally acidic or basic environments, or significant corrosion and abrasion, but are susceptible to cracking because of a higher sensitivity to temperature gradients [10]. For the purposes of UMass which resides in a temperate climate with vast variation between temperatures, a ceramic membrane is illogical. While metallic membranes exhibit remarkable permeability recovery after fouling, they can cause surface poisoning, and are much more expensive than polymer [10 & 13].

After the wastewater passes through the membrane, it undergoes the biological filtration process. A basic schematic of the operational process is shown in figure 2 [14]. Similar to the variety of membranes, there are also a variety of microorganisms that will optimize performance of the system. Selecting the correct microorganisms for the system is essential, otherwise complications can occur, such as: process overloads, variations in acidity, inhibition, foaming, rheological changes, and membrane surface fouling and clogging. Inhibition, or toxicity, can cause toxic shocks which decrease biological activity [11].

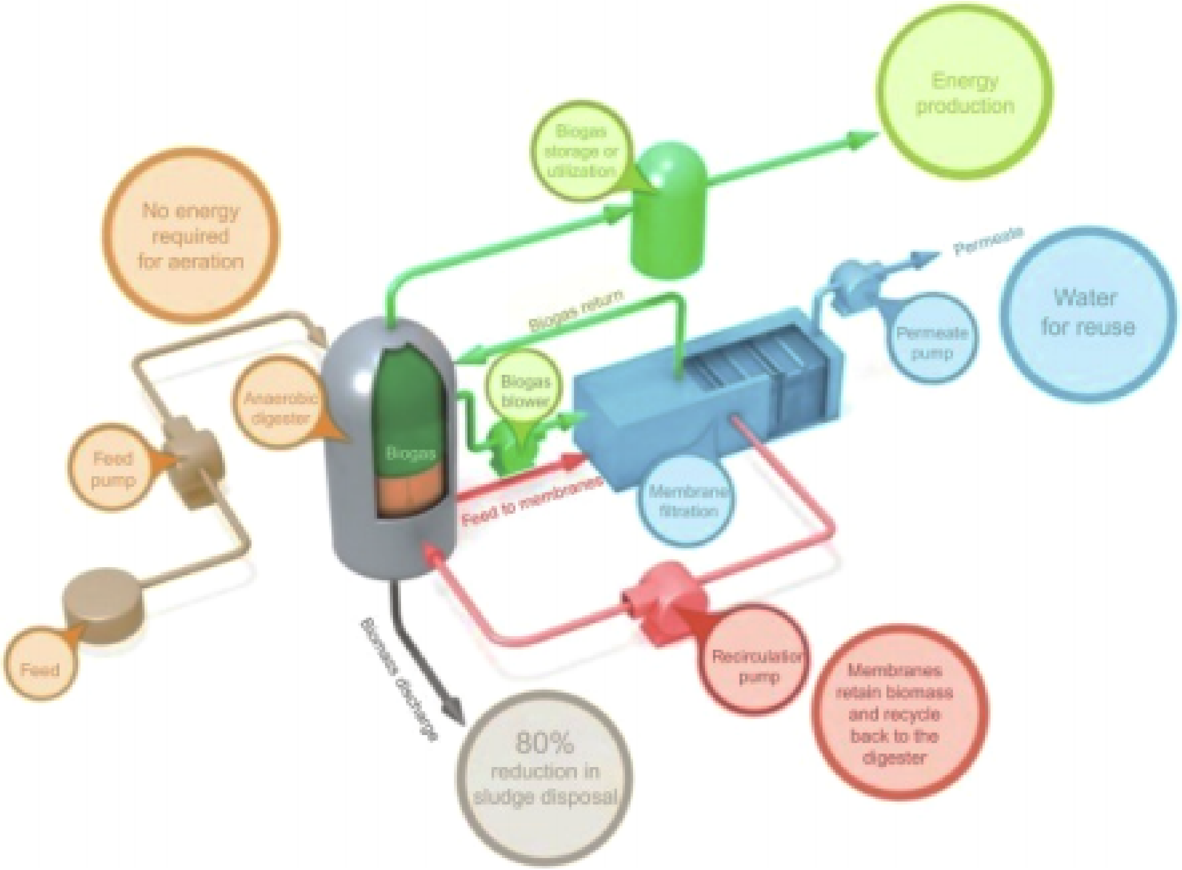


Figure 2: Basic operational design of an AnMBR

Implementation Specifications

Polymer is the best material for a membrane to serve the purposes of UMass, considering they are less expensive than ceramic and metallic, can withstand extreme temperature gradients, and have a variety of options to serve a specific purpose. Polymer membranes are typically derived from polyvinylidene difluoride (PVDF), but can include other types such as, but not limited to: Polyethersulfone (PES), polyethylene (PE), polypropylene (PP), and polysulfone (PSF) [14]. While it is important to consider that polymer membranes have lower permeability and are less stable compared to ceramic or metallic membranes under consistent chemical cleaning processes, with a side-stream configuration cleaning will be less frequent, thus ceramic or metallic membranes are not necessary [13].

Another aspect for consideration is the configuration of the membrane within the bioreactor. There are two types of configurations: Side-stream, and submerged. The submerged membrane utilizes a vacuum to pass the influent through the membrane. Using a vacuum requires no energy in order to move the influent through the membrane. However, this method requires complete disruption of filtration in order to provide chemical cleaning of the filtration cake that forms on the membrane over time. In the submerged configuration, formation of a filtration cake and flocculation can also occur more quickly, due to the lower shear force from the cross velocity of the water passing over the membrane.

The side-stream configuration of the membrane locates the membrane outside of the bioreactor. This requires use of a recirculation pump to pass the influent through the membrane, using more energy than the submerged membrane. While this uses more energy, having the membrane located outside of the bioreactor allows for access for cleaning and maintenance without complete disruption of the filtration process. The cross velocity passing over the membrane creates a higher shear force which allows flocculation and filtration cakes to form more infrequently, and less substantially, requiring less maintenance. For this purpose, UMass should use the side-stream configuration, despite the slightly higher energy usage.

Benefits and Drawbacks

LTHW has much to offer for our campus and its effort to achieve a net zero carbon footprint, the first and foremost upside being energy efficiency. LTHW could help UMass diminish wasted heat through steam, and make one of the most energy expensive infrastructures a more thermodynamically cyclical and wasteless system. As the pinnacle of UMass energy usage, retrofitting the CHP with an efficiency enhancement such as LTHW is crucial to achieving net zero.

The primary burdens of the implementation of LTHW come from the developmental phases. A bulk of the renovation required is in the piping infrastructure. As a result, necessary digging and subterranean construction will need to take place. In a similar project at Stanford (SESI), the university found that less than half of their current steam piping was reusable for hot water infrastructure, setting them up for a large scale operation to lay the foundation for new LTHW piping [12]. Evidently, underground construction is a disruptive and resource intensive procedure. Stanford found that it was a great burden to campus life by cutting off access to parts of campus and restricting foot traffic through important areas. Additionally, like any infrastructural change, a significant sum of capital investment is required. However, estimates claim the return on investment for LTHW could span just 10 years, as LTHW can save hundreds of thousands of dollars annually on energy costs [1].

Compatibly, one great benefit of using the AnMBR is that maintenance is more consolidated and safer than the current steam lines. Despite fouling being a major concern, the side stream configuration allows access more readily to the membrane and a simple chemical treatment can remove debris.

Another great benefit of an AnMBR is the production of biogas. This biogas could potentially be used to create a self-sustainable water treatment facility on campus. This would be the primary location where grey water is filtered to be used in LTHW lines. It could also potentially help reduce the CHPs dependence on non-renewable fuels. Once the CHP is fully transitioned away from burning natural gasses, this biogas could be sold as carbon offsets to other off-campus entities.

Looking ahead, LTHW shows promise in aiding the CHP in keeping heat distribution efficient; the system is reliable, modular, and can adapt to further retrofitted adjustments within heating and cooling infrastructure. However, AnMBRs are a relatively new technology. There is little research of these filters functioning at municipal scales. This means there is some risk involved and UMass would need to invest in research and development of this specific technology on campus in order to reap its benefits.

Conclusion

By retrofitting the CHP with the combined LTHW distribution and AnMBR filtered greywater, UMass could see 28.7% of its carbon emissions reduced [8]. The ultimate goal of supplying campus with more efficiently sourced and distributed heat must be met by tackling an underlying burden. The excessive water consumption of the proposed LTHW system is a significant impediment to the long term mission of mitigating resource consumption, and by using an AnMBR to filter and reuse campus sourced greywater, we can both decrease the water consumption and wasted energy of the CHP. Granted this concept is nascent, the potential for its impact on our campus is immense; as a result more research on the implementation of LTHW and AnMBR hybrid systems is necessary. While the costs and necessary investment to renovate

the CHP with the proposed solution are high and pose questions about its realistic efficacy [3], UMass has the opportunity to incorporate an innovative solution to college campus heating, and can serve as a model for other institutions and communities beyond the scope of just our region. The potential benefits greatly outweigh the potential drawbacks, and breaking barriers as a university and community will go a long way for UMass and the innovating world around it.

Appendix

Calculations

The following calculation was to determine the increase in water mass circulated through a LTHW system compared to the water mass circulated in the steam system. According to a report from the American Society of Heating, Refrigerating, and Air-Conditioning, in a study that compared water usage of buildings before and after retrofitting to LTHW systems from steam, there was a 79% decrease in water use [6]. This is related to the entire building, so it may be an assumption that the retrofit was entirely responsible for this observation, however, these calculations prove that the amount of circulated water does increase. The decrease in water utilization may be due to the increased efficiency of the LTHW system, or easier maintenance, fewer leaks and condensate.

Data from the CHP, which has an efficiency of 75% [7]. Here we assume that efficiency directly corresponds to the water mass circulated. The capacity of the CHP is 475,000lbs. Actual:
475,000lbs/hr (.75) = 356,250 lbs/hr

Thermodynamic equation used:
$Q = m\,c\,\Delta T$

Temperature of steam = T high = 100 C
Temperature of returning water = T low = 12 degree C
Specific heat capacity of steam = c = 2.03 (J/g*C)
Mass of water circulated in current stream system = 356,250 lbs/hr

Conversion using conversion factors:

m = 356,250 lbs/hr (1 kg / 2.2lb) = 161,931 kg/hr

161,931 kg/hr (1000g / 1 kg) = 162,000,000 g/hr

Q = 162,000,000 g (2.03 J/g*C) (12 C – 100 C)

Q = -65,772,000,000 J/hr This will be used in the following calculation to find the mass of liquid water circulated in the LTHW system, assuming the CHP efficiency stays at 75% its capacity.

Low temp hot water prediction

Thermodynamic equation used:

$Q = m\ c\ \Delta T$

Temperature of hot water = T high = 65 C

Temperature of returning water = T low = 12 C

Specific heat capacity of liquid water C = 4.148 (J/g*c)

-65,772,000,000 J / (4.148) (12 C - 65C) = m = 297,000,000 g/hr

Conversion using conversion factors:

297,000,000 g/hr (1 kg / 1000g) = 297,000 kg/hr

297,000 kg/hr (2.2 lb / 1 kg) = 594,000 lbs/hr

The steam system circulates 356,250 lbs/hr of steam whereas the LTHW theoretically circulates 594,000 lbs/hr. The switch between systems appears to cause an increase in circulated water.

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