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Energy Efficiency Potential of Nanofluids

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Definition of Terms and Acronyms

AHU – Air Handling Unit

AHRI – Air-Conditioning, Heating, and Refrigeration Institute

BAS – Building Automation System

BTU/hr – British Thermal Units per Hour, a measure of energy transfer

CCF – Hundred Cubic Feet (of Natural Gas)

CFM – Cubic Feet per Minute, a standard measurement of airflow

CIP – Conservation Improvement Program

CHW – Chilled Water

CHWP – Chilled Water Pump

CO_2 – Carbon Dioxide

CUSUM – Cumulative Sum

CWP – Condenser Water Pump

CWRT – Condenser Water Return Temperature

CWST – Condenser Water Supply Temperature

EFLH – Equivalent Full-load Hours

GPM – Gallons Per Minute, a standard measure of fluid flow in a pipe

HP – Horsepower

HWP – Hot Water Pump

HVAC – Heating, Ventilation, and Air Conditioning

HYDROMX PG – HYDROMX propylene glycol

Hz – Hertz, a standard measure of motor speed

IPLV – Integrated Part-Load Value, a method of rating equipment efficiency, particularly chillers

IPMVP – International Performance Measurement and Verification Protocol

kW – Kilowatt, a common measure of electric power

kWh – Kilowatt Hour, a common measure of electric energy

MAT – Mixed Air Temperature, the result of mixing outdoor air with room air in an air handling unit

MBH – 1,000 BTU per hour

MMBtu – 1,000,000 BTU per hour

NOAA – National Oceanic and Atmospheric Administration

OAT – Outdoor Air Temperature, commonly dry-bulb temperature

OA WB – Outdoor Air Wet-Bulb temperature, a standard measure of the moisture content in the ambient air

TMY – Typical Meteorological Year

TRM – Technical Reference Manual

VAV – Variable Air Volume

Executive Summary

Heating and cooling systems comprise a significant portion of a building's annual energy consumption. Many buildings and homes use water-sourced systems such as boilers, chillers, and heat pumps for heating and cooling. Hydronic systems may use glycol-water mixtures to prevent the freezing and bursting of pipes and coils in extreme weather conditions, such as those observed in Minnesota. When glycol is added to HVAC systems, it reduces the heating or cooling capacity as well as the efficiency of the system.

Nanofluids may present the potential to increase the efficiency of these systems in the state of Minnesota and beyond. Nanofluids are conventional fluids that contain suspended nanoparticles. Multiple scientific experiments and studies demonstrate that nanofluids exhibit improved thermal conductivity compared to conventional fluids. These findings raise the question: can the enhanced thermal conductivity of nanofluids increase the energy efficiency of hydronic HVAC systems?

This CARD study aimed to address that question by determining the impacts of a commercially available nanofluid called HYDROMX on HVAC system energy usage, maintenance, and thermal comfort.

Existing Research

Case studies for HYDROMX claim that chilled water and hot water energy consumption can be reduced by 20-40% by utilizing HYDROMX, resulting in paybacks of less than three years. However, these case studies generally lack information about the savings quantification methodology, specifically how the results account for varying weather conditions and building occupancy patterns. Individual case study data is shown in Table 1.

Table 1. Case Study Data

Location	Facility Type	Application	% Savings Results	Simple Payback	Duration	Methodology	Verification Potential (data quality)
New Delhi, India (Galaxy Energy Solutions LLP 2017)	Hotel	Heating Hot Water - Diesel Boiler	30.6%	<12 months	56 days	submetered data	Minimal - Output from Report
Jaipur, Rajasthan, India (Galaxy Energy Solutions LLP 2018)	Hospital	Chilled Water System	29%	34 months	12 days	submetered data	Posted Results in the report - no raw data

Location	Facility Type	Application	% Savings Results	Simple Payback	Duration	Methodology	Verification Potential (data quality)
Hosur Tamilnadu, India (Eco Energy Expert Services LLP 2017)	Pharm. Manufacturing	Chilled Water System	21-39%	n/a	Five months	daily submetered data	Marginal
Fargo, ND (HYDROMX 2018)	Data Center	CRAC Units with Fluid Coolers	32%	Nine months	Six months	change in compressor amps only from BAS data	No BAS data - PDF chart output
Turkey (PBA Energy Solutions Ltd 2015)	Government Staff Bldg	Space Heating with LPG Boilers	33.6%	n/a	entire season	weather normalized usage data comparison	No BAS data - PDF chart output
Unknown (PBA Energy Solutions Ltd 2011)	Oil Refinery	Space Heating	21.6%	n/a	entire season	weather normalized usage data comparison	No BAS data - PDF chart output
Great Britain (atega 2016)	Shelter (Multi-Unit)	Closed Heating System	24.73%	n/a	4-5 months	weather normalized usage data comparison	No BAS data - PDF chart output
Erzurum Province (HYDROMX 2010)	Military	Closed Heating System	35%	<2 years	unknown	single value claim	Testimonial from Customer
Fargo, ND (HYDROMX 2018)	Primary Education	Air-Cooled Chillers	39%	n/a	Two months	comparison of two similar schools	No BAS data - comparison of chiller kWh consumption
Hauppauge, NY (HYDROMX 2018)	Commercial Office	Data Center CRAC	27.29%	One year	unknown	appears to be metered data	Testimonial from Customer
Rye Brook, NY (HYDROMX 2018)	Commercial Office	Water Source Heat Pump	22%	<3 years	annual	costs normalized by occupancy and weather	Minimal - Output from Report

Location	Facility Type	Application	% Savings Results	Simple Payback	Duration	Methodology	Verification Potential (data quality)
Poole, England (HYDROMX n.d.)	Commercial Office	Space Heating	30.90%	n/a	unknown	weather normalized usage data comparison	Minimal - Output from Report
New Delhi, India (Galaxy Energy Solutions LLP 2016)	Hotel	Space Heating	22.60%	21 months	Three months	submetered data	Posted Results in the report - no raw data
Istanbul, Turkey (Seçilmiş 2015)	Shopping Mall	Air-Cooled Chilled Water System	22.50%	n/a	17 months	weather normalized usage data comparison	Posted Results in the report - no raw data
Jaisalmer, India (Galaxy Energy Solutions LLP n.d.)	Hotel	Hot Water System	40.30%	<1 year	unknown	unknown	Minimal, no source
Tamil Nadu, India (Galaxy Energy Solutions LLP 2018)	Manufacturing	Water-Cooled Chiller	24.1-26.3%	n/a	Two months	submetered data	Posted Results in the report - no raw data

Currently, at least two nanofluids projects have been studied by Minnesota utilities through their custom rebate programs. These projects utilized sub-metered data to quantify the energy use of the HVAC systems before and after the installation of the nanofluid. The project team reviewed the methodology and data for both analyses and deemed them accurate per our independent engineering judgment. However, the metering duration was still relatively short term. Results are shown in Table 2.

Table 2. MN Custom Rebate Analyses

Location	Facility Type	Application	% Savings Results	Simple Payback	Duration	Methodology	Verification Potential (data quality)
St. Paul, MN	University	Chilled Water System	9.5%	12 years	Two months	submetered data	High – raw data supplied

Location	Facility Type	Application	% Savings Results	Simple Payback	Duration	Methodology	Verification Potential (data quality)
Minneapolis, MN	Laboratory	Heat Recovery System	23.76%	0.95 years	One month	submetered data	High – raw data supplied

Methodology

This project aimed to address gaps in existing research by performing a field study to show the energy impacts of replacing water or water/glycol mixtures in HVAC systems with HYDROMX. The study also assessed the simple payback period of installing the nanofluid and any other non-energy impacts on the operation and maintenance of the HVAC systems.

Two different methodologies were used to quantify savings for commercial and residential applications. For commercial systems, the study utilized long-term sub-metering of HVAC equipment before and after the installation of HYDROMX. Building automation systems captured operating data for each system. This effort included the installation of additional metering points to collect all the necessary data to perform the efficiency analysis.

Commercial HVAC systems were then analyzed to determine the cooling or heating efficiency impacts of HYDROMX across various outdoor air temperatures and loading conditions. The energy input was compared to the heat supplied by the HVAC system to determine the in-field operating efficiency across the range of observed operating conditions. System efficiency is represented by kW per ton for chiller systems or therms of natural gas per mmBTU for boiler systems.

The project team used a whole facility regression modeling approach to quantify savings for residential sites. This approach was used because sub-metered data points were not readily available for residential sites. There is less variability in residential HVAC operations, which lends itself to a whole facility energy modeling approach. The project team developed regression models to fit the monthly natural gas usage against the average monthly temperature for each site before and after the installation of the nanofluid.

As shown in Table 3, six different HVAC systems at five sites were recruited for field testing.

Table 3. Site Summary

Site	Facility Description	Impacted System
Test Site 1 - Dakota County Administration Building	Municipal Administrative Building	Water-Cooled Chiller
Test Site 2 - Dakota County Administration Building - Addition	Municipal Administrative Building	Air-Cooled Chiller
Test Site 3 - Wooddale Dental Office	Dental Office	Hot Water Boiler (Non-Condensing)

Site	Facility Description	Impacted System
Test Site 4 - Courage Kenny Rehabilitation Institute	Healthcare and Rehabilitation Facility	Hot Water Boiler (Condensing)
Test Site 5 – Single Family Home	Single Family Residential	Hot Water Boiler (Condensing)
Test Site 6 – Four-Plex Building	Multi-Family Residential	Hot Water Boiler (Non-Condensing)

Results and Discussion

The results of each nanofluid installation are presented below in Table 4. These results are normalized for variances in weather to provide an accurate comparison of energy use.

Table 4. Results Summary

Site Name	System Type	Annual Energy Savings Estimate [a]	% Savings	Incremental Installation Cost	Operating Cost Reduction	Carbon Dioxide Reduction (lbs)	Simple Payback
Dakota County Administration	Water-Cooled Chiller	-6,927 kWh	-22%	$10,888	-$693	-3,380	N/A
Dakota County Administration	Air-Cooled Chiller	1,278 kWh	9%	$24,120	$128	624	188.7
Wooddale Dental	Non-Condensing Hot Water Boiler	426 Therms	29%	$7,035	$315	4,960	22.3
Courage Kenny	Condensing Hot Water Boiler	-2,368 Therms	-14%	$7,404	-$1,752	-27,589	N/A
Residential Single Family	Condensing Boiler	9 Therms	1%	$620	$6.30	99	98.3
Residential Four-Plex	Non-Condensing Boiler	-124 Therms	-5%	$804	-$91	-1,439	N/A

a) Chiller systems correspond to kWh electric savings. Boiler systems correspond to therms of natural gas.

The annual energy savings varied from -22% to 29%, with no discernable trends. Chiller and boiler systems showed savings and an increase in energy use, depending on the facility. The residential systems also showed savings and an increase in energy use. The study could not determine why some sites showed savings while others exhibited an increase in energy consumption.

The incremental cost of HYDROMX fluid was compared to the energy cost savings to determine the simple payback period for each installation. The payback period ranged from 22 to nearly 190 years for sites exhibiting energy savings. The sites exhibited significant variations in the size of the HVAC system fluid loops. The payback period is highly correlated to the size of the loop, as larger loops require more gallons of nanofluid which directly increases the project cost.

Participants at the nanofluid test sites were also surveyed about potential changes to building comfort, maintenance impacts, occupancy patterns, and heating and cooling control set points. None of the sites reported any changes to occupancy patterns during the testing. However, two of the sites changed equipment operating schedules. This change was likely due to the unoccupied nature of the facilities during the COVID-19 pandemic. Most sites saw no change in maintenance activity related to the nanofluid installation. However, three sites experienced malfunctioning equipment unrelated to the nanofluid installation. None of the sites reported a positive or negative change to building thermal comfort after nanofluid installation.

Confidence in Results

The study was carried out using industry best practices to capture data at a level precise enough to pinpoint issues with the monitoring. However, the project team encountered many real-world challenges in performing the analysis. These issues included occupancy impacts due to the COVID-19 pandemic, issues with data quality, and challenges recruiting test sites on time.

The impacts of COVID-19 were observed through the monitoring conducted in this study. The monitoring was carried out from February 2020 to May 2022. Due to activity restrictions, many buildings were unoccupied for part or all of the test period. The low occupancy led to two issues. First, some occupancy changes likely happened that the project team was unaware of during the study. Control sequence and occupancy schedule changes appear to have occurred based on the data collected from building automation systems. However, our contacts at these test facilities could not pinpoint when specific changes were made to the control system.

Second, many of these HVAC systems exhibited low loading conditions that would not reflect standard operations. Commercial building loads, in many cases, did not exceed 25% of the system capacity. In comparison, the load on a typical system might peak around 80% of system capacity. The study was designed to determine the efficiency of each system at various loads with and without using nanofluids. However, the efficiency and response of systems at the lower limits of their loading range can exhibit some odd behavior, which may be a factor in the results of this study. The project team was unaware of any feasible alterations to the study design that could have been utilized to account for the low-loading conditions of the HVAC equipment.

Despite the challenges encountered during the metering of these HVAC systems, the project team believes some meaningful results were obtained from this study. The project team’s qualitative estimation of the confidence in results for each site is summarized below:

- The Dakota County water-cooled chiller demonstrated fluid foaming after the nanofluid installation. It was discovered that an air bleeder valve was not installed on the chiller loop after the installation of the nanofluid. Foaming of the fluid would inhibit heat transfer. The foaming could explain why the system operated less efficiently than it did previously with water installed in the loop. When the system was drained, no foaming was observed in the loop. Because of this, confidence in these results is low, as the foaming issue may have negated any efficiency benefit.

- After installing the nanofluid, the Dakota County air-cooled chiller system showed an efficiency gain. An alternative water-side analysis also showed savings, although to a lesser degree than the air-side analysis. The confidence in these results is relatively high.

- The Wooddale Dental boiler system showed an increase in efficiency due to the installation of the nanofluid. However, it was discovered that some additional heating coils existed in the system that were thought to be disconnected. Because of this, the project team had to assume that the load on those coils did not change. We also conducted an alternative water-side analysis on this site, which showed no impact on the system's energy consumption. Due to these factors, the confidence in these results is relatively low.

- The Courage Kenny boiler system was the most complicated system monitored. The boiler system supplies heat to the domestic hot water system, the space heating coils, the swimming pool, and the outdoor snow melt system. The study’s approach attempted to control for these variables; however, this system pushed the limits of the analysis approach. The project team cannot explain why energy consumption increased at this site. The confidence in the results at Courage Kenny is medium.

- The residential sites used a more straightforward billing analysis approach to calculate savings. The nanofluid installation had more minor impacts on residential HVAC energy consumption than commercial systems. The residential facilities also have less variability in their operation than the commercial sites as they are continuously occupied. Therefore, there are fewer factors that might have an unforeseen impact on the energy analysis. The confidence in the savings values for the two residential sites is high.

Conclusions and Recommendations

Due to the variance of the savings observed at each site, the overall findings of this study are inconclusive. The results from the residential sites were relatively consistent and had fewer issues. The project team has more confidence in these results. However, the installation of nanofluids at the residential sites showed minimal impact on energy consumption. Conversely, the commercial sites experienced more issues and showed a wider variability in the energy impacts due to nanofluid installation. As a result, the project team has lower confidence in those results.

Because of the variability in the results of this study, the project team does not suggest developing a prescriptive measure for inclusion in the Minnesota Technical Reference Manual (TRM) at this time. In the project team’s opinion, measures for the TRM need to exhibit repeatable savings. The small number of test sites studied in this project and the variability in savings observed do not conclude that savings are repeatable.

However, based on some of the sites' findings, the project team believes there is potential for savings using this technology. Utility custom efficiency programs are most suitable for nanofluid projects at the current time. The project team suggests that custom rebates be contingent upon monitored results to verify the achieved energy savings, as the results depend on many variables. However, monitoring the energy impacts of these types of projects is complex, which can cause delays in getting incentive dollars to utility customers.

The project team recommends that the nanofluid technology be pursued further based on some of the findings in this study and the theoretical research that other laboratories have previously conducted. It is known that nanofluids can speed up the transfer of heat. Still, this study could not conclusively determine that faster heat transfer directly translates to a reduction in energy usage. The project team hypothesizes that the increased heat transfer could allow for more aggressive energy savings control sequences. However, studying the interaction between control strategies and nanofluids was beyond this study's scope.

The project team recommends that nanofluids be tested in a controlled laboratory environment to determine if nanofluids can speed up heat transfer and create overall energy savings. These tests could precisely control each variable and determine the exact conditions in which nanofluids lead to energy savings.

Introduction

Water-sourced HVAC systems such as boilers, chillers, and water-source heat pumps are ubiquitous in larger facilities. These systems typically use water as a heat transfer medium. They may also utilize water-glycol mixtures to provide freeze protection where HVAC coils are exposed to below-freezing air temperatures. When HVAC systems are run with a glycol mixture, it derates the capacity and efficiency of the system. Derating occurs because a glycol-water mixture has a lower specific heat than water alone, meaning each pound of fluid can hold and transfer less heat.

Nanofluids are fluids in which nanoparticles are suspended within conventional fluids, such as glycol, to improve the thermal conduction behavior. Nanofluids exhibit enhanced thermal conductivity and convective heat transfer coefficients compared to the base fluid alone. Therefore, can nanofluids increase the efficiency of HVAC systems in real-world applications?

This project aimed to determine the reduction in HVAC energy consumption due to utilizing HYDROMX nanofluid in various real-world HVAC applications in Minnesota. This goal was accomplished through long-term sub-metering of the HVAC equipment with and without HYDROMX. The analysis methodology follows industry best practices specified by the International Performance Measurement and Verification Protocol (IPMVP). The study also assessed product cost-effectiveness and any impacts on the operation and maintenance of the HVAC systems.

HYDROMX is a commercially available heat transfer nanofluid that contains stably suspended nanoparticles to increase the speed of heat transfer. The manufacturer claims nanoparticles rearrange the molecular structure of the fluid, improving thermal conductivity. HYDROMX is claimed to be most suitable for closed-loop heating and cooling systems. Efficiency will be theoretically achieved by transferring energy in a shorter time, reducing the run-time of associated equipment, and, in theory, reducing energy usage. The manufacturer also claims HYDROMX will increase equipment life and reduce maintenance expenses.

Case studies claim that the energy consumption of HVAC systems can be reduced by 10-35% by replacing the existing fluids with HYDROMX, resulting in paybacks of less than three years (HYDROMX n.d.). Academic lab studies have tested the fluid in steady-state conditions and estimate savings between 10% and 50%, depending on the application and experiment setup. While these case studies exist, the project team has been unable to find any transparent case studies conducted by US engineering companies. A long-term field study with transparent data showing the effects of utilizing this nanofluid technology could help provide clarity for the marketplace.

Nanofluid Theory

Using the suspension of solids to increase the thermal conduction behavior of fluids is a concept over a century old (Maxwell 1873). However, the suspension of macro- or micro-sized particles leads to several disadvantages:

1. The particles settle rapidly, forming a layer on the surface, thus reducing heat transfer.
2. Increased circulation rates decrease settling but increase the erosion of heat transfer devices and piping.
3. The large size of particles tends to clog cooling channels.
4. The presence of particles increases the pressure drop of the pumping system considerably.

Improved manufacturing technologies have led to nanofluids' development, which has overcome many of these disadvantages. Modern materials provide the ability to produce nanometer-sized (<100 nm) particles that behave differently from the parent material's mechanical and thermal properties.

Nanofluids exhibit enhanced thermoconductivity, far beyond expectations and much higher than any theory could predict. Even similar fluids with micrometer-sized particles suspended within the fluid do not exhibit the same heat transfer enhancement. The mechanism of thermal conductivity enhancement in nanofluids is still unclear. Many attempts to identify and model this mechanism have been unsuccessful (Das, Choi and Patel 2006). Some models have been able to predict individual applications accurately. However, there does not appear to be a single theory that can explain the anomalous heat transfer enhancement effects in nanofluids that have been reported (Kaggwa and Carson 2019). An in-depth discussion of this modeling is beyond the scope of this paper.

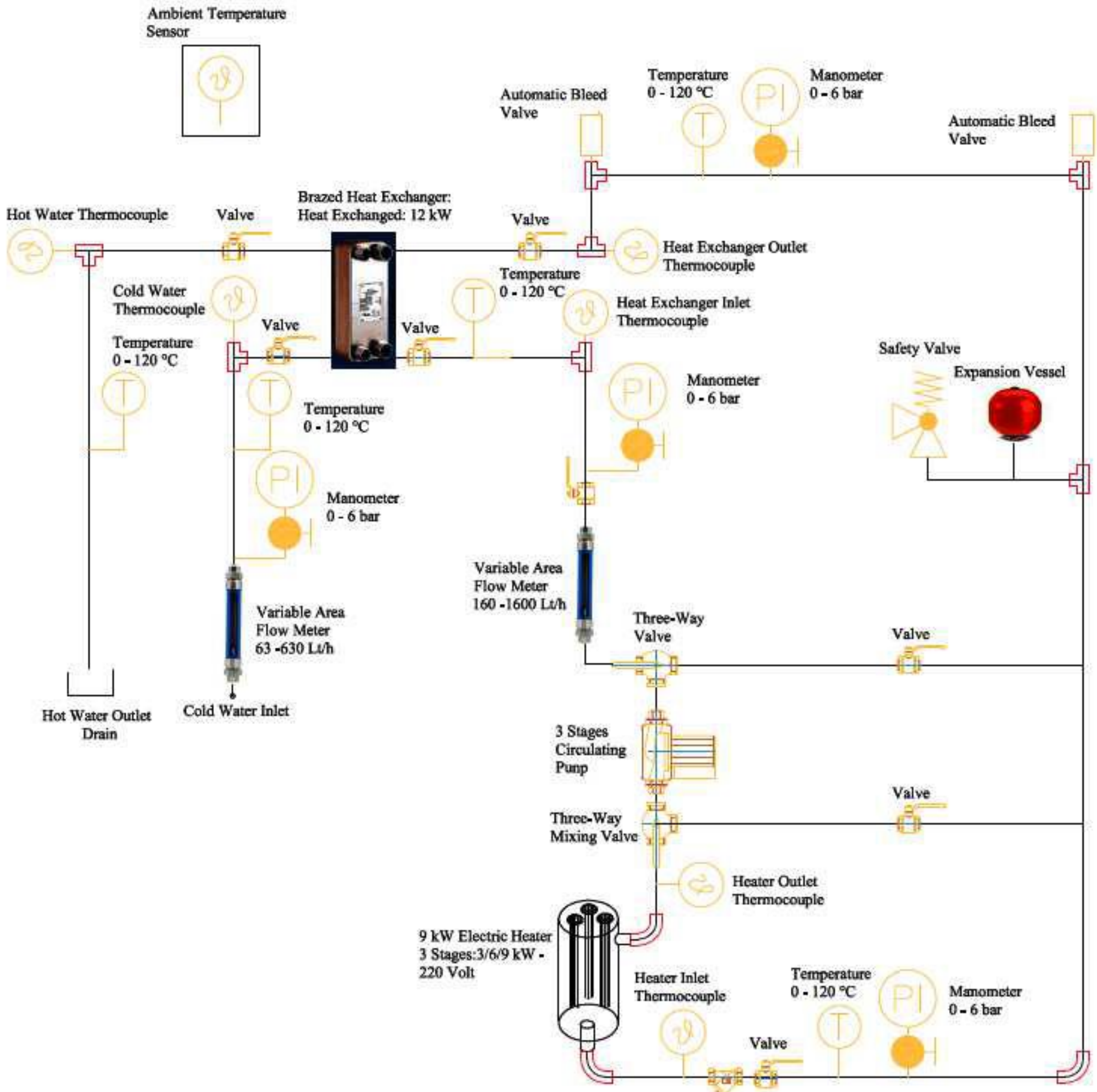
Many existing studies demonstrate the enhanced thermal conductivity of nanofluids. However, they stop short of quantifying the energy impacts of utilizing them in HVAC applications. The following section of this report summarizes laboratory tests, case studies, and Minnesota utility rebate data that attempts to quantify the savings due to utilizing nanofluids in various applications.

Laboratory Tests

Kocaeli University Test

The Kocaeli University Asım Kocabıyık Vocational School of Higher Education Heating and Cooling Laboratory in the Republic of Turkey conducted several experiments to determine the performance of the HYDROMX. Heat transfer rates were analyzed and compared for 100% water and 50% water/50% HYDROMX solution in a closed-loop brazed plate heat exchanger with eight plates and a total heat transfer surface of 0.84 square meters. Tap water was used as the secondary (cold) fluid at various flow rates in the experiment. The primary fluid flow rate and heat input were kept constant at 1,100 Liters/hour and 9 kW. Figure 1 depicts the experimental setup used by the University to conduct the tests.

Figure 1. Experiment Setup



The tables below show selected data findings from the Kocaeli University Test.

Table 5. Test Data Using Water as the Primary Fluid

Cold Water Fluid Flow (liter/hr)	Primary Fluid delta T (°C)	Cold water delta T (°C)	Log Mean delta T (°C)	Heater Input Watts	Ratio of Cold Water Input to Heater Watts
400	4.97	18.02	11.783	8,746	0.948
350	4.93	20.75	12.438	8,670	0.974
300	4.48	23.76	13.175	8,680	0.955
250	4.51	28.68	14.77	8,560	0.974
200	4.61	36.96	16.714	8,646	0.987

Table 6. Test Data Using 50:50 Water/HYDROMX as the Primary Fluid

Cold Water Fluid Flow (liter/hr)	Primary Fluid delta T (°C)	Cold water delta T (°C)	Log Mean delta T (°C)	Heater Input Watts	Ratio of Cold Water Input to Heater Watts
400	6.14	17.74	12.925	8,697	0.948
350	6.05	21.32	13.549	8,670	1.001
300	5.61	24.73	14.192	8,728	0.988
250	5.87	30.46	15.747	8,790	1.007
200	5.84	39.12	18.244	8,650	1.052

Table 7. Percent Increase Between Water and HYDROMX

Cold Water Fluid Flow (liter/hr)	Primary Fluid delta T (°C)	Cold water delta T (°C)	Log Mean delta T (°C)	Heater Input Watts	Ratio of Cold Water Input to Heater Watts
400	23.54%	-1.55%	9.69%	-0.56%	0.00%
350	22.72%	2.75%	8.93%	0.00%	2.77%
300	25.22%	4.08%	7.72%	0.55%	3.46%
250	30.16%	6.21%	6.61%	2.69%	3.39%
200	26.68%	5.84%	9.15%	0.05%	6.59%

The Kocaeli University Test concluded, in part, the following:

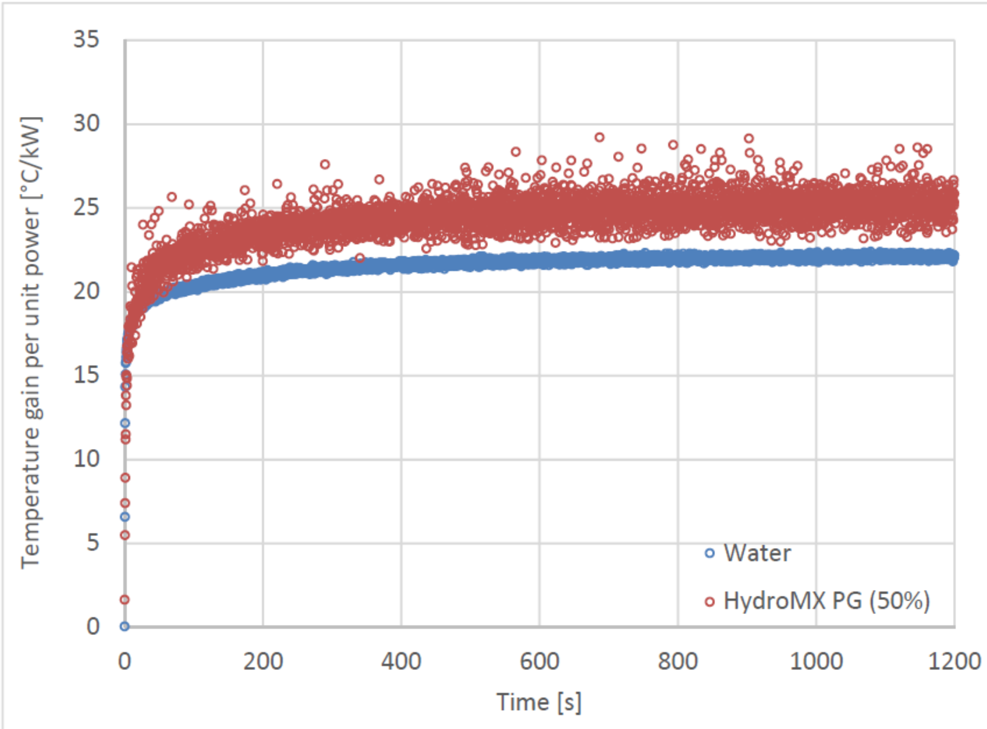
- The logarithmic mean temperature difference using the HYDROMX solution was 8% higher than water in the brazed plate heat exchanger setup.
- As a result, the heat transfer rate increased by up to 6.59% using the HYDROMX solution compared to water in the experiment.
- The analysis of the experimental results indicates that the temperature of the HYDROMX solution and the system's improved performance does not depend only on the thermal conductivity and specific thermal capacity values. The fluid's physical and chemical properties also affect heat transfer performance. Notably, the thermal performance of the HYDROMX solution compared to water increases with the rise in flow rates and fluid temperature (Secilmis 2012).

The Kocaeli University Test concluded that the heat transfer capacity through the brazed plate heat exchanger was approximately 8% greater when using the HYDROMX/water solution than water alone. It does not, however, make any claims to increase overall system efficiency.

University of North Dakota Test

Researchers at the University of North Dakota conducted testing on HYDROMX. Details regarding the test setup and background were not available. However, the following figure and summary of the test are shown in Figure 2.

Figure 2. Example Chart from the University of North Dakota Study



Temperature gain (delta T) in fluid per 1 kW of heat input for flow at 5.0 fps; on average, the delta T for Hydromx PG (50%) is about 14.0% higher than water.

Key highlights from the University of North Dakota Test are as follows:

- HYDROMX propylene glycol (PG) mixed with 50% water has a higher temperature gain per unit of heat input than water at the same flow velocity between 0.5 and 5 feet per second (fps).
- The temperature difference for HYDROMX PG (50%) is, on average, 13% higher than for water, between 0.5 and 5 fps flow velocity.
- The HYDROMX PG (50%) temperature gain curves are more scattered than the curves for water.
- This scatter suggests a higher level of fluctuation in the HYDROMX PG (50%) flows, which may be caused by the presence of nanoparticles in the HYDROMX PG (50%).
- Generally, the higher level of fluctuation can be attributed to a higher level of mixing in the flow, which promotes heat transfer (Tang 2018).

HYDROMX Case Studies

The project team gathered HYDROMX case studies from the vendor and other sources and summarized them in Table 8.

Table 8. Case Study Summary

Location	Facility Type	Application	% Savings Results	Simple Payback	Duration	Methodology	Verification Potential (data quality)
New Delhi, India (Galaxy Energy Solutions LLP 2017)	Hotel	Heating Hot Water - Diesel Boiler	30.6%	<12 months	56 days	submetered data	Minimal - Output from Report
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Hosur Tamilnadu, India (Eco Energy Expert Services LLP 2017)	Pharm. Manufacturing	Chilled Water System	21-39%	n/a	Five months	daily submetered data	Marginal
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Jaisalmer, India (Galaxy Energy Solutions LLP n.d.)	Hotel	Hot Water System	40.30%	<1 year	unknown	unknown	Minimal, no source

Location	Facility Type	Application	% Savings Results	Simple Payback	Duration	Methodology	Verification Potential (data quality)
Tamil Nadu, India (Galaxy Energy Solutions LLP 2018)	Manufacturing	Water-Cooled Chiller	24.1-26.3%	n/a	Two months	submetered data	Posted Results in the report - no raw data

The case studies show percent savings ranging from about 20-40%, with an average savings of 28.4%. There does not appear to be any correlation of savings to the HVAC system type, as both chilled water and hot water systems show savings ranging from 20-40%. The case studies did not provide enough detail to determine potential reasons for the variation in savings observed.

Some of the case studies did detail their methodology for calculating savings, while others did not and only present savings values without explanation. None of the case studies provided enough detail to recreate the savings values independently. Nor did they discuss normalizing savings for weather or other non-routine events that could affect energy consumption in the facilities studied. In general, it does not appear that any case studies quantified the operating efficiency of the heating or cooling equipment before and after installing HYDROMX fluid.

Analyses in Minnesota

To the project team's knowledge at the time of writing, two nanofluids projects have been studied by Minnesota utilities through their custom rebate programs. These projects utilized sub-metered data to quantify the energy use of the HVAC systems before and after the installation of the nanofluid. The project team reviewed the methodology and data for both analyses and deemed them accurate per our independent engineering judgment.

Table 9 summarizes the results of a nanofluid retrofit on a chilled water system.

Table 9. Water-Cooled Chiller Retrofit Results

Facility Type	University
Application	Water-cooled Chilled Water System
Baseline Fluid	30% ethylene glycol mixture
Project Cost	$22,464
Annual Savings	5,306 kWh
Percent Savings	9.5%

Payback Period	12 years
Methodology	Sub-metered data
Metering Duration	Two months pre and post

Table 10 summarizes the results of a nanofluid retrofit on a run-around coil heat recovery system.

Table 10. Laboratory Heat Recovery Retrofit Results

Facility Type	Laboratory
Application	Heat Recovery Loop
Baseline Fluid	50% ethylene glycol mixture
Project Cost	$2,380
Annual Savings	990 kWh and 3,585 therms
Percent Savings	23.76%
Payback Period	0.95 years
Methodology	Sub-metered data
Metering Duration	One month pre and post

Both installations showed savings by replacing the existing glycol/water mixture with a nanofluid/water mixture. However, the payback period varies significantly between the two applications. This variation appears to be due to at least two factors:

- The chilled water system has a larger loop, as evidenced by the installation cost, which is nearly ten times that of the heat recovery loop.
- The chilled water system operates only during the cooling season. In contrast, the heat recovery loop operates year-round, providing heating and cooling savings.

Based on these findings, the fluid loop's size and the affected HVAC system's operating hours should be considered when considering the installation of nanofluids.

Methodology

This study aimed to provide field test results on the effects of using nanofluids as a heat transfer medium in different HVAC system types. Four different system types were targeted for testing: a commercial chiller, a commercial condensing boiler, a commercial non-condensing boiler, and a residential boiler. Ultimately, six different HVAC systems at five sites were recruited for field testing. Table 11 summarizes the test sites recruited to participate in the study.

Table 11. Test Site Summary

Site	Facility Description	Impacted System
Test Site 1 - Dakota County Administration Building	Municipal Administrative Building	Water-Cooled Chiller
Test Site 2 - Dakota County Administration Building – Addition [b]	Municipal Administrative Building	Air-Cooled Chiller
Test Site 3 - Wooddale Dental Office	Dental Office	Hot Water Boiler (Non-Condensing)
Test Site 4 - Courage Kenny Rehabilitation Institute	Healthcare and Rehabilitation Facility	Hot Water Boiler (Condensing)
Test Site 5 – Single Family Home	Single Family Residential	Hot Water Boiler (Condensing)
Test Site 6 – Four-Plex Building	Multi-Family Residential	Hot Water Boiler (Non-Condensing)

b) Test Site 1 and Site 2 are technically the same facility; Site 2 is an addition to Site 1 and is served by a separate chiller system.

This study's goal was to determine the effects of nanofluids on system efficiency across the range of operating conditions. In other words, answering whether or not utilizing a nanofluid for heat transfer in water-source HVAC systems leads to energy savings. Two separate data collection plans were formulated to answer that question: one for commercial systems and one for residential systems.

For commercial systems, the energy input was compared to the HVAC system's heat transfer to determine the in-field operating efficiency. This analysis followed the International Performance Measurement and Verification Protocol (IPMVP) Option B: Retrofit Isolation (All Parameter Measurement) methodology.

The operating data for each commercial HVAC system was captured from the facilities' building automation systems. In some cases, additional metering points were installed to collect all necessary data to perform the efficiency analysis. Data was downloaded at regular intervals or obtained from the facility owners as they could provide it to the project team.

Per the nanofluid manufacturer, the heat transfer of their product cannot be quantified using standard heat transfer equations that rely on the specific heat of the water. However, the project team could not find a source substantiating that claim from other research organizations. Therefore, each analysis utilized alternative approaches (such as air-side analyses) to quantify the systems' heat transfer without utilizing the nanofluid's specific heat. Where possible, water-side heat transfer calculations were included as a comparison.

There appears to be some validity to the manufacturer’s claim about the viability of using water-side energy analysis equations. HYDROMX is purported to make the fluid behave as a non-Newtonian fluid with highly variable properties, making it no longer a constant between the two compared cases.

For residential sites, a whole facility energy modeling approach was used because submetered data were not readily available, and there was less variability in operation. This methodology complies with IPMVP option C: Whole Facility Method. Energy usage was normalized for the different weather conditions across the test periods to ensure a fair comparison.

Each site’s unique HVAC system, equipment, and system details are described in the following section. Data logging parameters for each site are covered in Appendix B: Analysis Methodology.

Test Site Information

Site 1 – Dakota County Water-Cooled Chiller

The Dakota County test site is a county municipal administrative building. The facility contains office space for municipal workers. The system consists of a single water-cooled chiller and constant-speed chilled water pumps that supply water to the air handling units.

A constant volume condenser water loop carries the heat removed from the building spaces by the cooling coils and the heat generated by the chiller compressor to two open-circuit cooling towers. The cooling towers reject heat from the chiller with variable-speed cooling tower fans that modulate speed to maintain a fixed condenser water set point. A system diagram is shown in Figure 3, and a picture of the chiller is shown in Figure 4.

Figure 3. Water-Cooled Chilled Water System

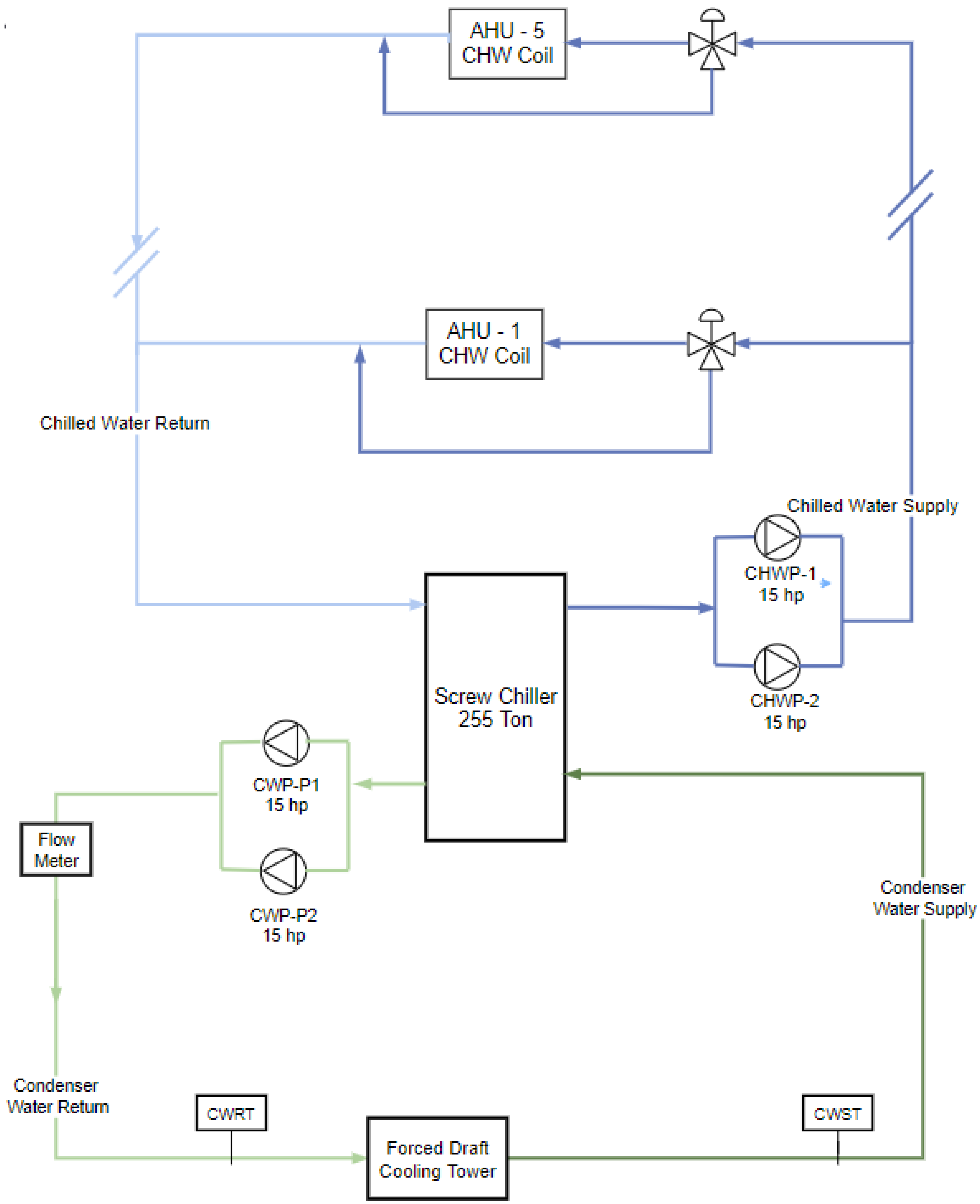


Figure 4. Water-Cooled Chiller

Site 2 – Dakota County Air-Cooled Chiller

The Dakota County Annex is an addition to the Dakota County Administration facility and functions as a municipal office building. A separate chilled water plant provides cooling to a variable volume air handler dedicated to the addition.

The chilled water plant consists of an air-cooled chiller with a rotary screw compressor. Redundant constant-speed pumps deliver chilled water to the air handler. The air handler contains a three-way valve to control chilled water input to the cooling coil. The system's current heat transfer fluid is a mixture of 30% ethylene glycol and 70% water. Figure 5 shows a diagram of the air-cooled system, and Figure 6 shows the air-cooled chiller.

Figure 5. Air-Cooled Chilled Water System

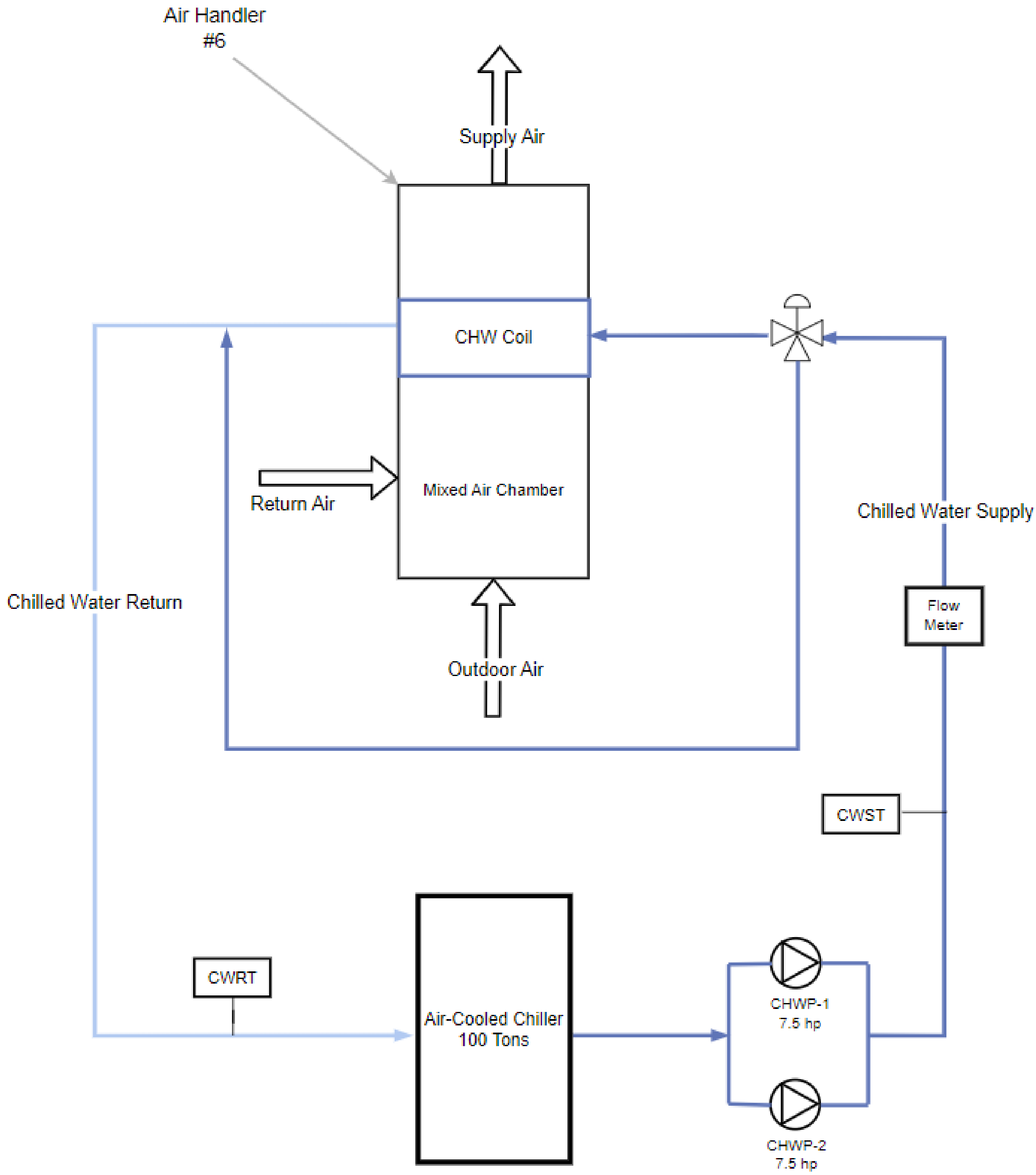


Figure 6. Air-Cooled Chiller

Site 3 – Wooddale Dental Non-Condensing Boiler

The Wooddale Dental site consists of a two-story building housing a dental office. The facility heating system is a hot water system supplied by one natural gas, non-condensing boiler. Hot water is distributed with two constant-speed circulation pumps. The air-side system consists of a variable volume air handler with terminal hot water reheat coils. The original system design includes hot water radiant panels, initially assumed to be deactivated. Figure 7 shows a hot water system diagram, and Figure 8 shows the boiler.

Figure 7. Hot Water System Diagram

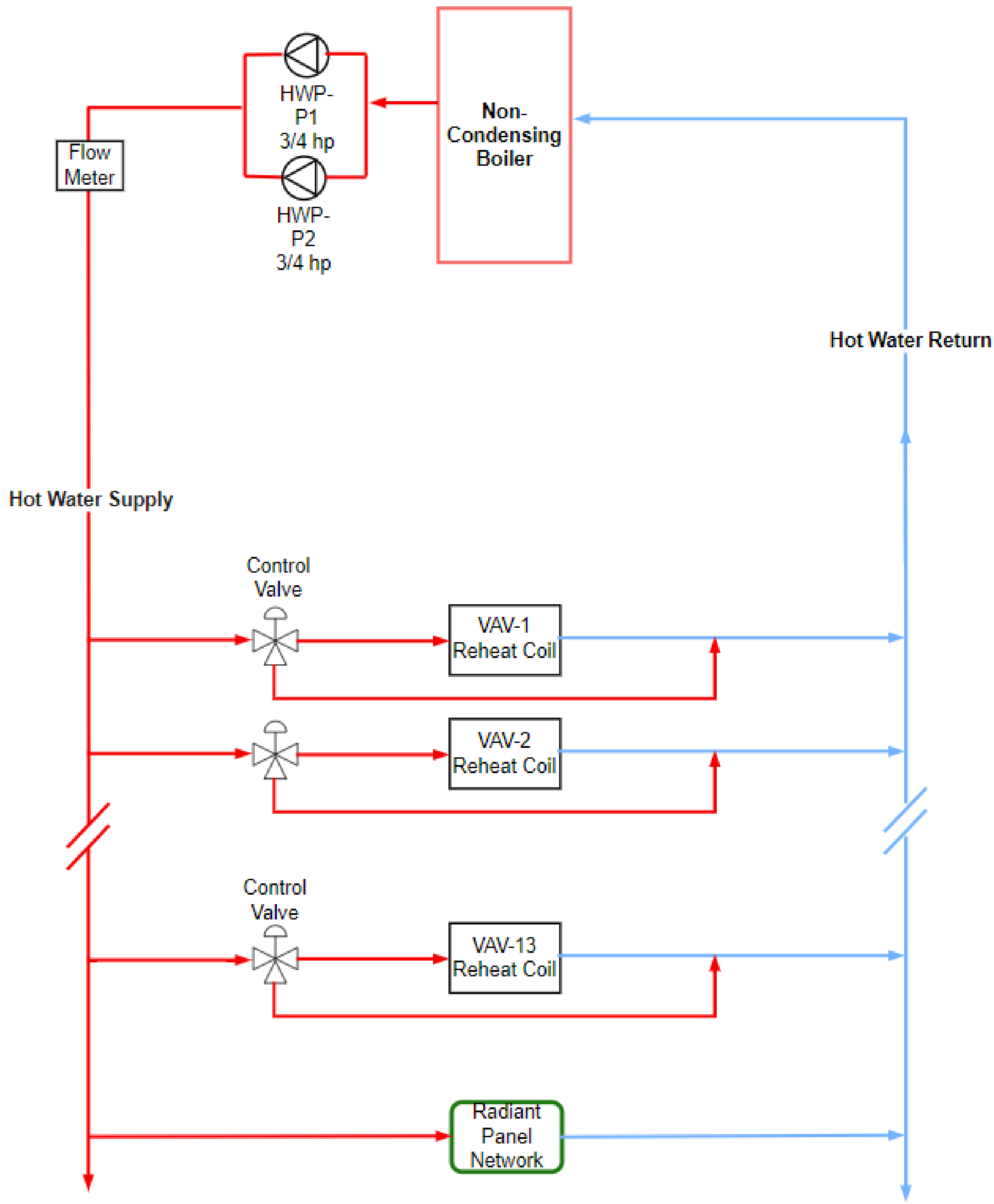


Figure 8. Non-Condensing Boiler

Site 4 – Courage Kenny Condensing Boiler

Courage Kenny is a healthcare and rehabilitation facility. It houses a variety of treatment areas, including a therapy pool.

The heating system consists of four condensing boilers that supply a primary hot water loop. This loop contains pure water. Heat is then transferred to four sub-loops serving air handlers, domestic hot water, snow melt, and a pool heating system. The air handler and snowmelt loops contained a mixture of approximately 40% glycol and 60% water. Figure 9 shows the hot water system diagram, and Figure 10 shows the boilers.

Figure 9. Hot Water System Diagram

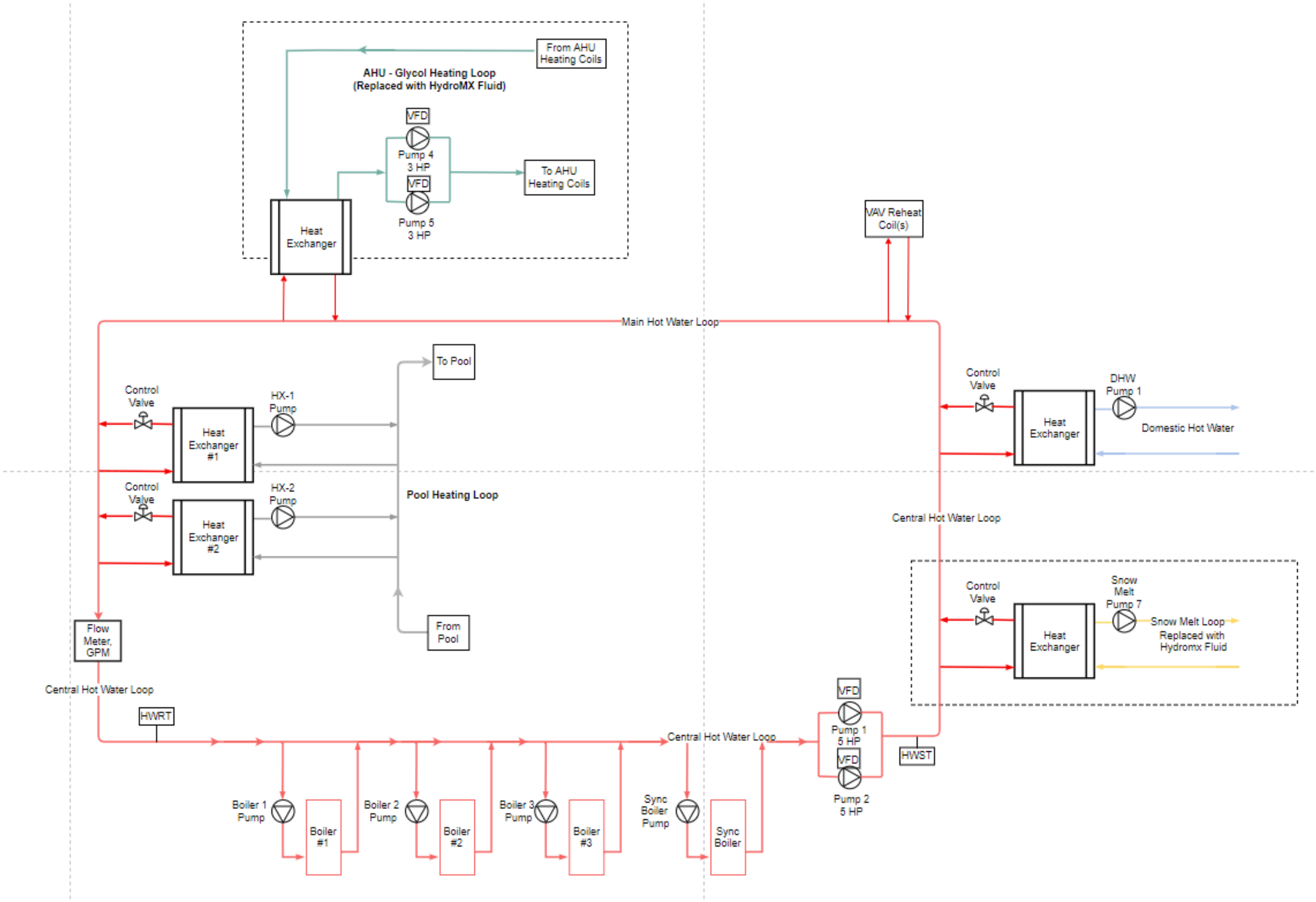


Figure 10. Condensing Hot Water Boilers

Site 5 – Residential Single-Family Condensing Boiler

Test site 5 is a two-story single-family private residence. The home utilizes a hot water heating system supplied by a condensing hot water boiler. The boiler serves an air handler with two hot water coils: one serving the lower level and the other serving the upper level. The boiler also provides heat to the domestic hot water tank in the household. The boiler is set to provide 135°F hot water and was approximately one year old when the study began.

The system's baseline working fluid is water. The thermostats are not programmed to utilize nighttime temperature setbacks; the temperature is held constant at 73°F during the heating season. Additional natural gas use at the site includes a clothes dryer, gas grill, and gas unit heater in the garage. The boiler is shown in Figure 11.

Figure 11 Condensing Boiler and Distribution Piping

Site 6 – Residential Four-Plex Non-Condensing Boiler

Test site 6 is a multiple-family residence with four separate dwelling units. The brick-constructed building was built in 1965. It contains a 150,000 BTU/hr non-condensing boiler that is original to the building and circulates water to baseboard radiation heating equipment in each apartment. The hot water supply is set to provide 180°F hot water continuously. Other natural gas loads at the site include a domestic water heater and clothes dryer. The boiler is shown in Figure 12.

Figure 12. Non-Condensing Boiler and Water Heater

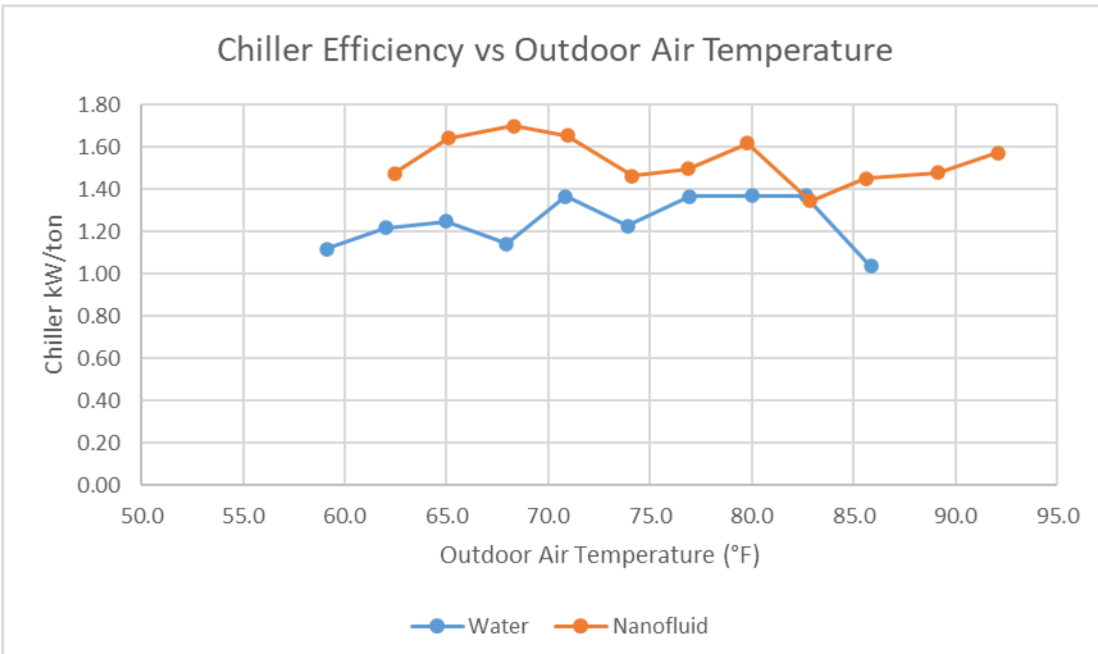
Results and Discussion

Site Level Energy Impacts

Site 1 – Dakota County Water-Cooled Chiller

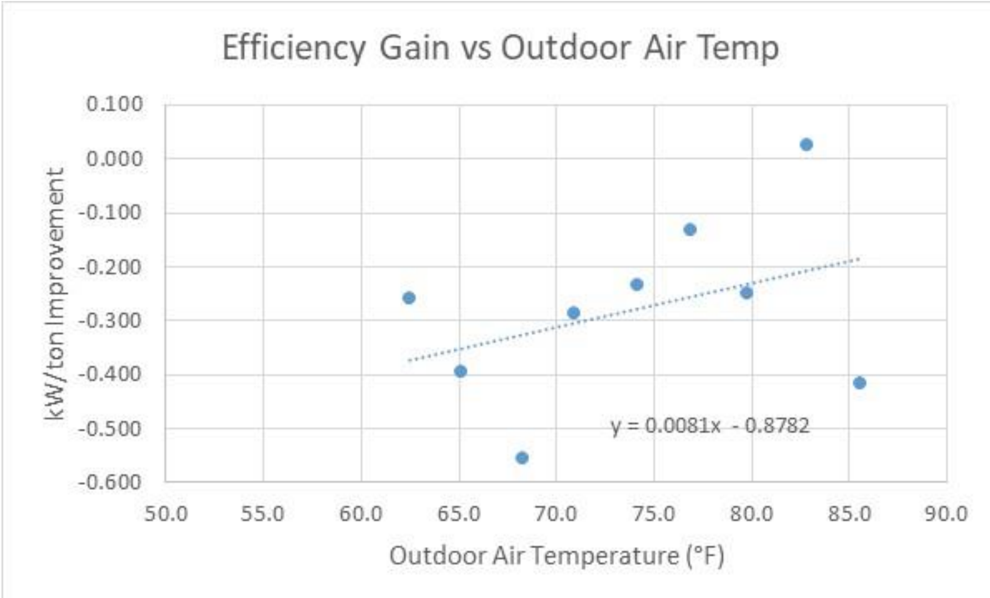
A graphical comparison of the chiller efficiencies in the baseline (water) and nanofluid metering periods across a range of outdoor air temperatures is shown in Figure 13. Unfortunately, the baseline data set did not include outdoor air dry bulb temperatures above 87°F.

Figure 13. Chiller Efficiency vs Outdoor Air Temperature



The chiller system's efficiency change was regressed against the outdoor air temperature, yielding the curve shown in Figure 14. The decrease in efficiency varies by outdoor air temperature bin but without a discernable correlation to weather conditions.

Figure 14. Efficiency Gain vs Outdoor Air Temperature



Annual Savings Estimates

An efficiency regression (shown in Figure 14) was used to determine the system's efficiency gain across the range of operating conditions. The baseline energy consumption of the system was normalized to the operating conditions observed during the nanofluid operation by applying the efficiency gain regression curve. This approach yielded an energy penalty of approximately 22%, or an additional 6,927 kWh use, as shown in Table 12 below.

Table 12. Water-Cooled Chiller Savings in 2021

Data Point	Result
Water kWh	32,167
Nanofluid kWh	39.094
Annual kWh Savings	-6,927
Percent Savings	-22%
Annual Carbon Savings (lbs)	-3,380
Simple Payback (Years)	N/A

Since the loading of the chiller system was abnormally low due to COVID-19 impacts, the savings were also calculated using the Minnesota Technical Reference Manual Version 3.3 methodology. Table 13 shows these results.

Table 13. TRM Water-Cooled Chiller Savings

Parameter	Value
Nanofluid IPLV	1.43 kW/ton
Water IPLV	1.17 kW/ton
Equivalent Full Load Hours (EFLH)	446 hours
Chiller Capacity	255 Tons
Minnesota TRM Equivalent Annual Savings	-28,776 kWh
Annual Carbon Savings	-14,043 lbs
Simple Payback	N/A

The chiller's integrated part-load values (IPLVs) using water and the nanofluid were estimated using the average calculated kW/ton across the monitoring periods. This average efficiency was determined by dividing the kWh consumed by the total ton-hours of cooling produced by the chiller.

The building served by the system is a low-rise structure in Zone 3; therefore, the calculation used 446 EFLH, as specified by the TRM. This methodology shows that a typical cooling season would likely have four times the cooling load observed during the late summer of 2021, as the chiller only ran 107 EFLH during this monitoring period.

Discussion

The chiller's rated efficiency is 0.82 kW/ton based. However, the calculated efficiencies do not approach this rating. The metered data shows the chiller efficiency closer to 1.3 kW/ton on average, which is approximately 0.5 kW/ton higher than the rated values. The calculated chiller efficiency in the baseline case ranged from 1.0 to 1.4 kW/ton. The calculated efficiency using nanofluids ranged from 1.3 to 1.7 kW/ton. Several factors may contribute to this discrepancy.

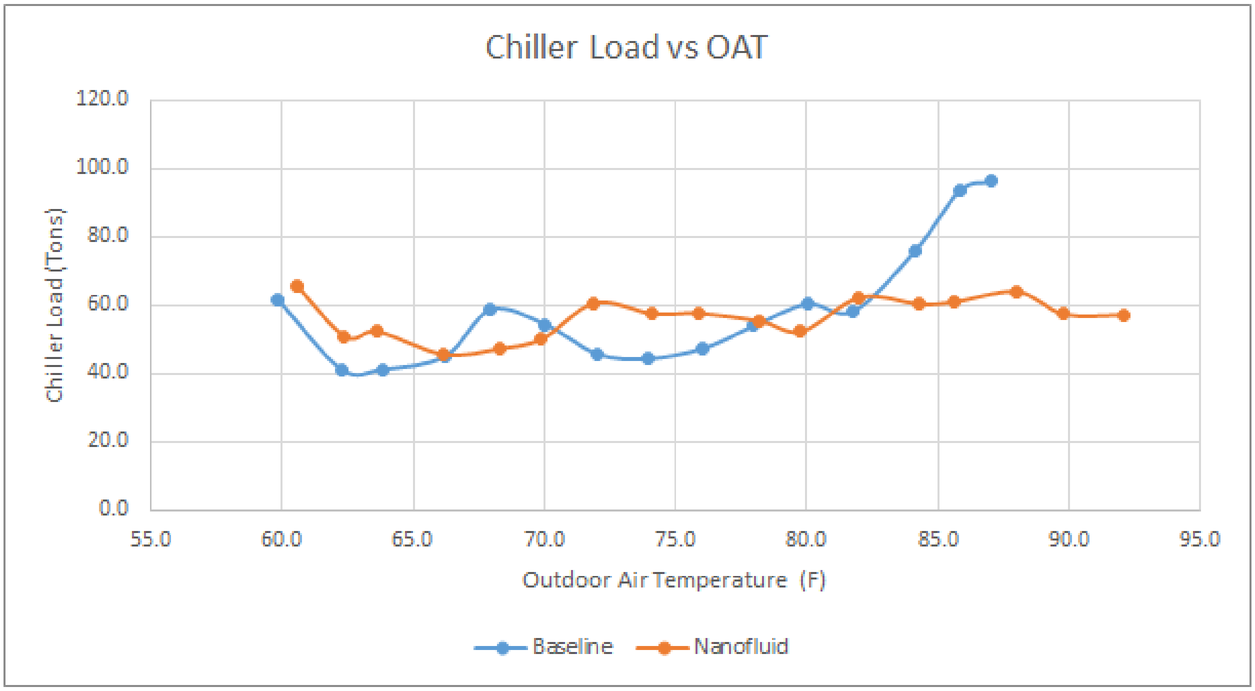
First, this system was missing a vent required to purge air from the water loop. In the baseline condition, air pockets in the loop may have inhibited heat transfer. However, the lack of an air vent was not noticed until after the nanofluid installation and foaming issues were detected. Attempts were made to correct the issue; however, the nanofluid data collection period included periods where the fluid foaming reduced heat transfer effectiveness. A follow-up fluid sample was drawn in early September 2022. Figure 15 shows that mitigation efforts have not yet resolved the issue as of this writing.

Figure 15. Nanofluid Foaming (Right) Compared to the Expected Appearance

It is also possible that there were additional unsolved maintenance issues with this chiller system contributing to the high kW/ton values observed during this study.

Additionally, this chiller operated at low loads throughout the monitoring period. Operating the chiller at low loads can impact the chiller's efficiency, particularly chillers with screw compressors of this vintage. The chiller is a Trane model RTHA255 with a cooling capacity of 255 tons and is approximately 32 years old. Figure 16 shows that the calculated chilled water loads approach 100 tons of cooling or 40% of the chiller capacity at the higher temperature bins in the baseline condition. Peak observed loads in the nanofluid period were less than 25% of the chiller capacity. The higher loading in the baseline condition is conducive to better compressor efficiency. No clear explanation could be determined for the difference in loading between the baseline and nanofluid periods, as the building occupancy patterns did not change significantly between 2020 and 2021.

Figure 16. Chiller Load vs Outdoor Air Temperature (OAT)



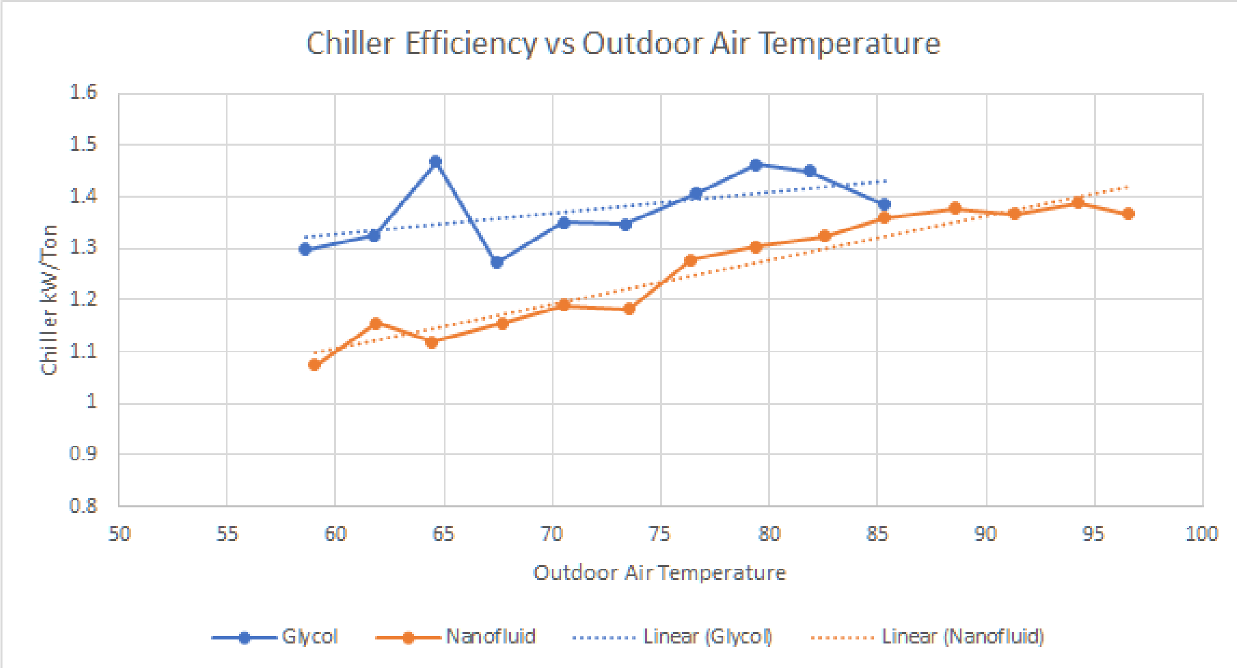
The low loading is likely due to the facility being mostly unoccupied during COVID-19. The data indicated that the chiller control sequence included a reset of the chilled water temperature, which further reduced the cooling load seen by the chiller. On average, the chiller return water temperatures were less than five degrees higher than the supply water temperature, about half the typical design conditions. Low return water temperature can also lead to efficiency degradation.

As detailed in Appendix B: Analysis Methodology, the chiller power calculation assumes a power factor of 0.78. While the actual power factor could have varied significantly from the assumed value, such a discrepancy would not explain the relationship between the baseline and nanofluid cooling efficiencies. As calculated for this study, the average chiller efficiency decreased by 0.28 kW/ton between the baseline and nanofluid periods. An incorrect power factor assumption would not explain this, as this power factor should be consistent across both the baseline and nanofluid operating periods.

Site 2 – Dakota County Air-Cooled Chiller

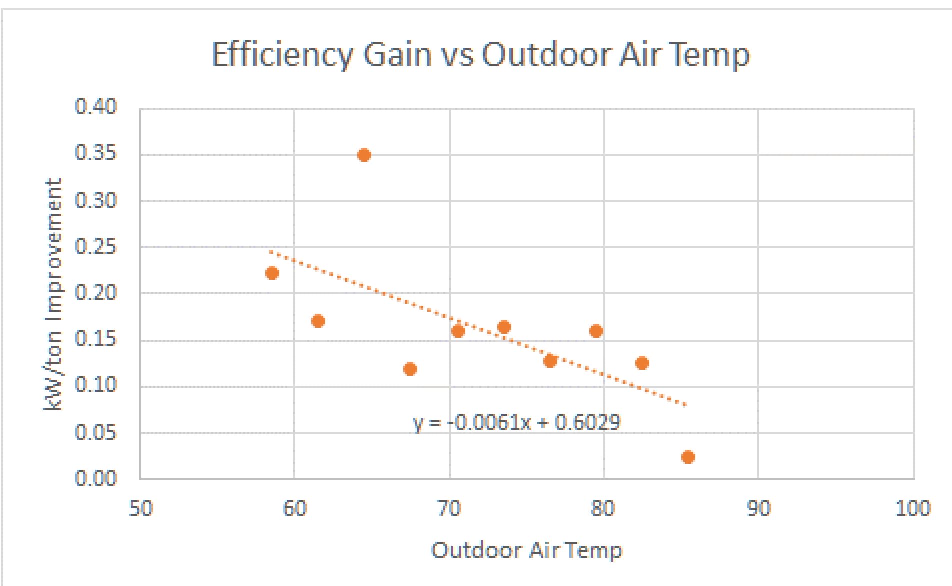
The nanofluid installation for site two resulted in energy savings or a more efficient (lower) kW/ton. The efficiency gains in each temperature bin average 0.16 kW/ton. While linear trends show more considerable efficiency gains at lower outdoor air temperatures and loadings, the efficiency increased at all temperature ranges after the nanofluid installation. A graphical comparison of the chiller efficiency across a range of outdoor air temperatures is shown in Figure 17.

Figure 17. Chiller Efficiency vs Outdoor Air Temperature



The chiller system's efficiency gain was regressed against outdoor air temperature, yielding the curve shown in Figure 18. The trend shows a more significant efficiency increase at lower outdoor air temperatures and loads than in peak loading conditions.

Figure 18. Efficiency Gain vs Outdoor Air Temperature



Annual Savings Estimates

An efficiency regression curve, plotting the efficiency impacts of the nanofluid installation against the outdoor air temperature (shown in Figure 18), was used to determine the system's efficiency gain across the range of operating conditions. The baseline energy consumption of the system was normalized to the operating conditions observed during the nanofluid operation by applying the efficiency gain regression curve to the metered data observed in the summer of 2021 for the nanofluid monitoring period. This approach yielded a savings of approximately 9% across the summer, or 1,278 kWh, as shown in Table 14.

Table 14. Air-Cooled Chiller Savings in 2021

Data Point	Result
Nanofluid kWh	13,682
Glycol kWh	14,960
kWh Savings	1,278
Percent Savings	9%
Annual Carbon Savings (lbs)	624
Simple Payback (Years)	189

Since the loading of the chiller system was abnormally low due to COVID-19 impacts, savings were also calculated using the Minnesota Technical Reference Manual Version 3.3 methodology.

Table 15. TRM Water-Cooled Chiller Savings

Parameter	Value
Nanofluid IPLV	1.22 kW/ton
Glycol IPLV	1.33 kW/ton
Equivalent Full Load Hours (EFLH)	446 hours
Chiller Capacity	100 tons
Minnesota TRM Equivalent Annual Savings	5,077 kWh
Annual Carbon Savings	2,478 lbs
Simple Payback	47.5 years

The chiller system's integrated part-load value (IPLV) was estimated using the average kW/ton across the operating seasons. The IPLV was calculated by dividing the average kWh consumed by the total ton-hours of cooling produced. The facility is a low-rise office building in zone 3; therefore, the calculation used 446 EFLH. As shown in Table 15, the TRM methodology shows that a typical cooling season would likely have four times the cooling load observed during the summer of 2021, as the chiller only ran 112 EFLH.

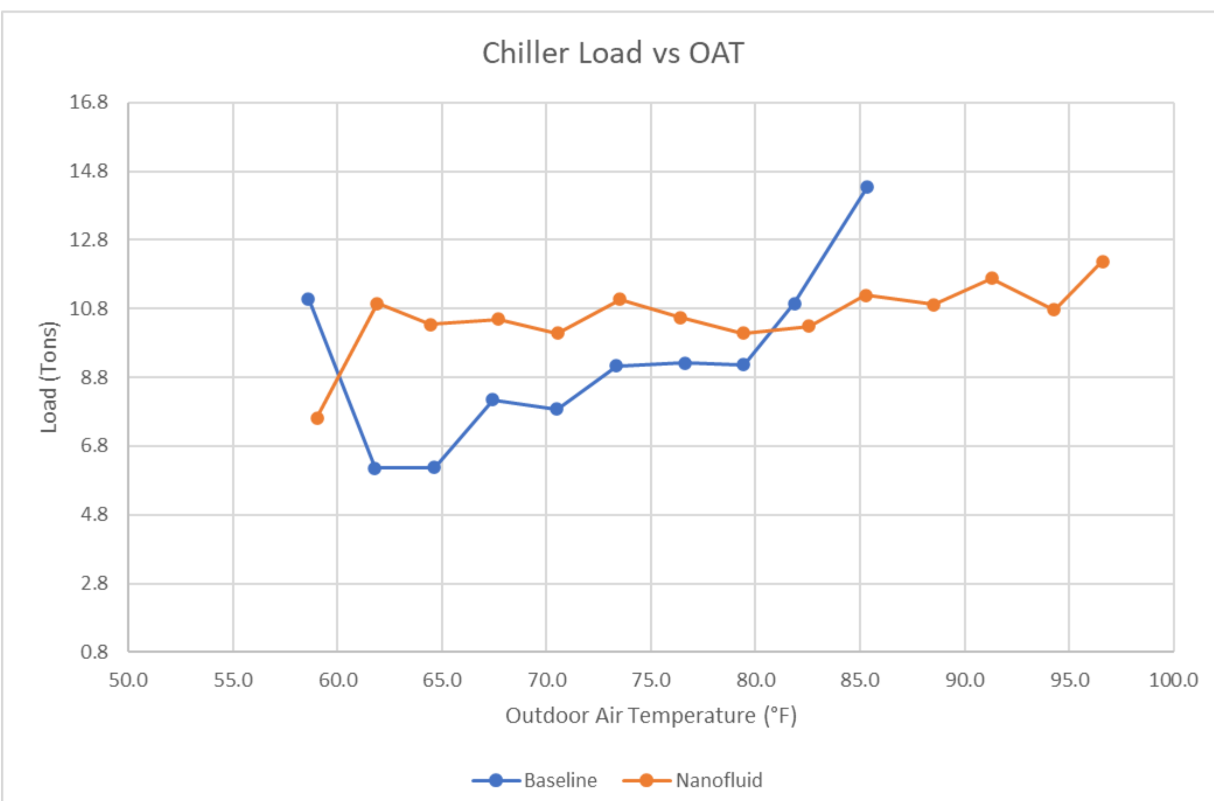
Discussion

The chiller's cooling capacity is nominally rated at 100 tons with a rated efficiency of 1.23 kW/ton at 95°F outdoor air temperature. The metered data show the chiller efficiency closer to 1.4 kW/ton, approximately 0.2 kW/ton higher than rated values.

This discrepancy could be due to the low loading on the system. As shown in Figure 19, the average load calculated by the outdoor air temperature bin during the metering period did not exceed 15 tons in any temperature bin. The calculated instantaneous cooling never exceeded 25 tons. The low load is likely because the facility was largely unoccupied due to COVID-19 during most of 2020 and 2021.

Additionally, the observed chilled return water temperature was often five degrees higher than the supply water temperature, or about half of the typical design conditions. Low return water temperature can lead to efficiency degradation. It is possible that fouling of the chiller heat exchangers could also be degrading the performance. However, the facility manager indicated that they performed regular maintenance on the system.

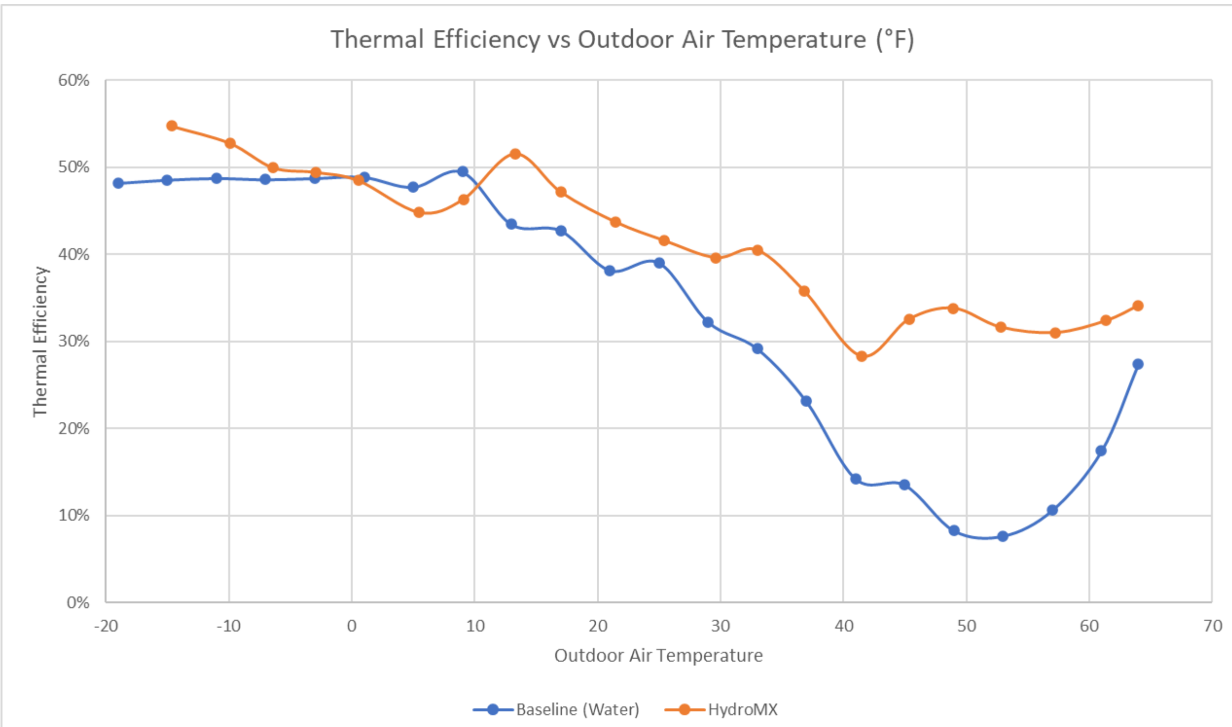
Figure 19. Chiller Load vs Outdoor Air Temperature (OAT)



Site 3 – Wooddale Dental Non-Condensing Boiler

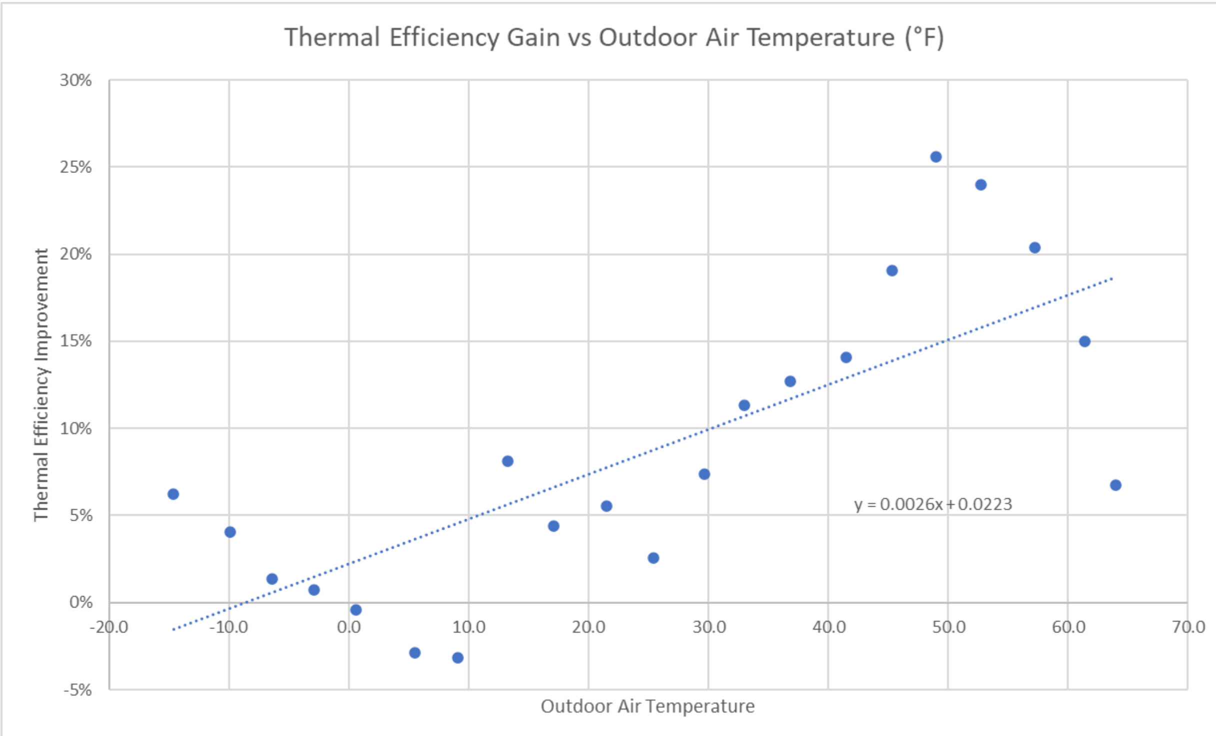
A graphical comparison of the heating system's calculated thermal efficiency using both the water and nanofluid across the range of (dry bulb) outdoor air temperatures are shown in Figure 20. Note that the calculated thermal efficiencies are much lower than expected. The heating load from radiant panels at this site was not captured, as the project team was told that the panels were no longer utilized. Unfortunately, after data was retrieved, the project team found the panels functioning on the digital automation system.

Figure 20. Thermal Efficiency Comparison



After the nanofluid installation, the heating system's efficiency gain was regressed against outdoor air dry-bulb temperature yielding the curve shown in Figure 21.

Figure 21. Thermal Efficiency Gain



The data analysis shows that the increase in the calculated thermal efficiency after nanofluid installation is most significant in mild conditions where heating loads are the lightest. However, the incomplete data makes it hard to draw conclusions from this site confidently.

Annual Savings Estimates

An efficiency regression curve, plotting the efficiency impacts of the nanofluid installation against the outdoor air temperature (shown in Figure 21), was used to determine the system's efficiency gain across the range of operating conditions. The boiler's efficiency gain regression was applied to the 2021 heating season metered data to determine the system's theoretical energy consumption using the nanofluid. This approach yielded a savings of approximately 29% across the year, or 426 Therms, as shown in Table 16.

Table 16. Non-Condensing Boiler Savings in 2022

Parameter	Result
Water Therms	1,878
Nanofluid Therms	1,452
Annual Therm Savings	426
Percent Savings	29%

Parameter	Result
Annual Carbon Savings (lbs)	4,960
Simple Payback (Years)	22.3 years

Since the calculated loading of the boiler system was abnormally low, savings were also calculated using Minnesota Technical Reference Manual Version 3.3 methodology. Table 17 contains these results.

Table 17. TRM Boiler Savings

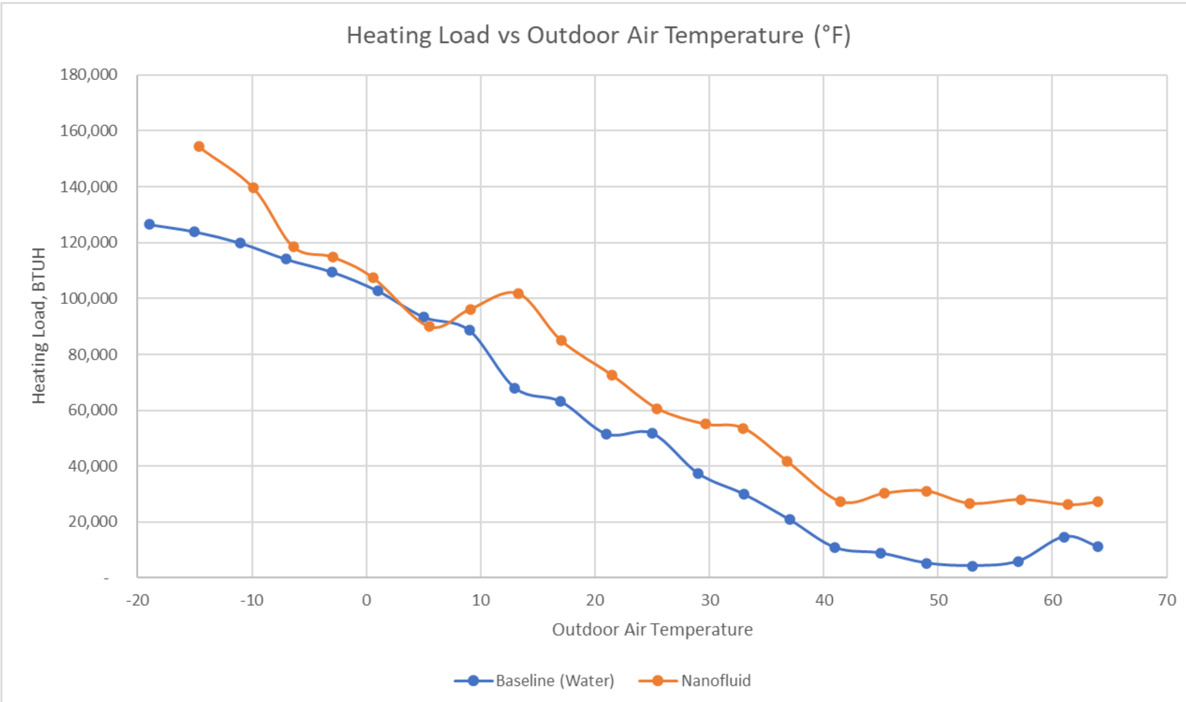
Parameter	Value
Average Efficiency - Water	40%
Average Efficiency - Nanofluid	52%
Equivalent Full Load Hours (EFLH)	1,830 hours
Boiler Capacity	521,700 MBH
Minnesota TRM Equivalent Annual Savings	5,417 Therms
Annual Carbon Savings	63,103 lbs
Simple Payback	1.8 years

The average efficiency of the boiler system using water and the nanofluid was determined by dividing the total gas consumed by the served heating load. The facility is a low-rise office building in zone 3; therefore, the calculation used 1,830 EFLH. The TRM methodology shows that a typical heating season would likely have 12 times the heating load observed during 2021, as the boiler only ran 146 EFLH. This EFLH value, however, does not include any operation during the night and weekend periods and does not include the load on the radiant panel system.

Discussion

The Wooddale Dental boiler's rated heating capacity is 600,000 BTU/hr. The calculated heating loads correlate to outdoor air temperature, as expected. However, the maximum load registered from the variable air volume (VAV) reheat coils in the baseline condition is less than 25% of this boiler capacity. Figure 22 shows this relationship. This low figure is likely due to additional loads from other systems that were not captured during metered data collection. The BAS reported active radiant panels tied to the hot water system. The team was told by site personnel that these panels were no longer used during the development of the metering plan. Unfortunately, the BAS did not report on data associated with the panels, such as water valve position or temperature. Building plans containing equipment capacities were not available for the panels. Adding additional data logging points to capture the load from the radiant panels was not feasible with the deployed metering plan.

Figure 22. Heating Load vs Outdoor Air Temperature

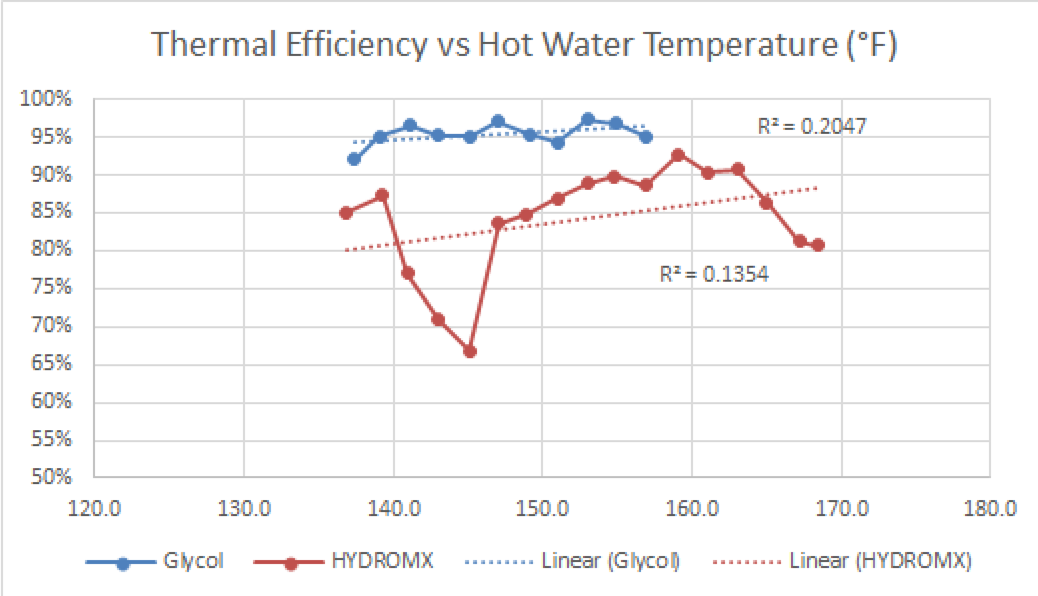


The boiler's input rating is 750,000 BTU/hr with a thermal efficiency of 80% at full load. The efficiency profiles calculated in both the baseline and nanofluid data collection periods are far lower (30-40% efficient in most outdoor air temperature bins) than the rated efficiency of the boiler. This finding is not necessarily surprising, as the load from the radiant panels was not included in the efficiency calculations, while the total input of natural gas into the boiler was. It was impossible to discern if the load from the radiant panels changed between the baseline and nanofluid monitoring periods. If the radiant load remained constant, the efficiency increase observed could be considered valid. Because of this, it is hard to draw any conclusions from this site for the study.

Site 4 – Courage Kenny Condensing Boiler

A graphical comparison of the heating system's thermal efficiency for both the glycol and nanofluid periods across a range of hot water temperatures is shown in Figure 23. Hot water supply temperature bins summarize the Courage Kenny condensing boiler operation to present the data. Hot water supply temperature was selected instead of outdoor air temperature because the boiler load does not correlate to ambient weather. The calculated efficiency in the nanofluid condition is considerably lower than the baseline.

Figure 23. Thermal Efficiency Comparison



Annual Savings Estimate

Table 18. Seasonal Gas Consumption Comparison

Parameter	Result
Glycol Therms	17,499
Nanofluid Therms	19,868
Therm Savings	-2,368
Percent Savings	-14%
Annual Carbon Savings (lbs)	-27,589
Simple Payback (Years)	N/A

Table 18 compares the calculated energy consumption between the glycol (2021) and the nanofluid (2022) periods. The estimated consumption does not span an entire year. It represents the energy required to serve the loads on the building loop from January 2022 through April 2022.

As shown in Figure 23 above, the measured thermal efficiency of the system did not vary by hot water supply temperature. For this reason, an average efficiency value of 96% was applied to the 2022 load profile, as calculated in Table 18, to estimate the normalized glycol energy consumption compared to the nanofluid operation. This approach yielded an energy penalty of approximately 14% across the summer or an additional 2,368 Therms.

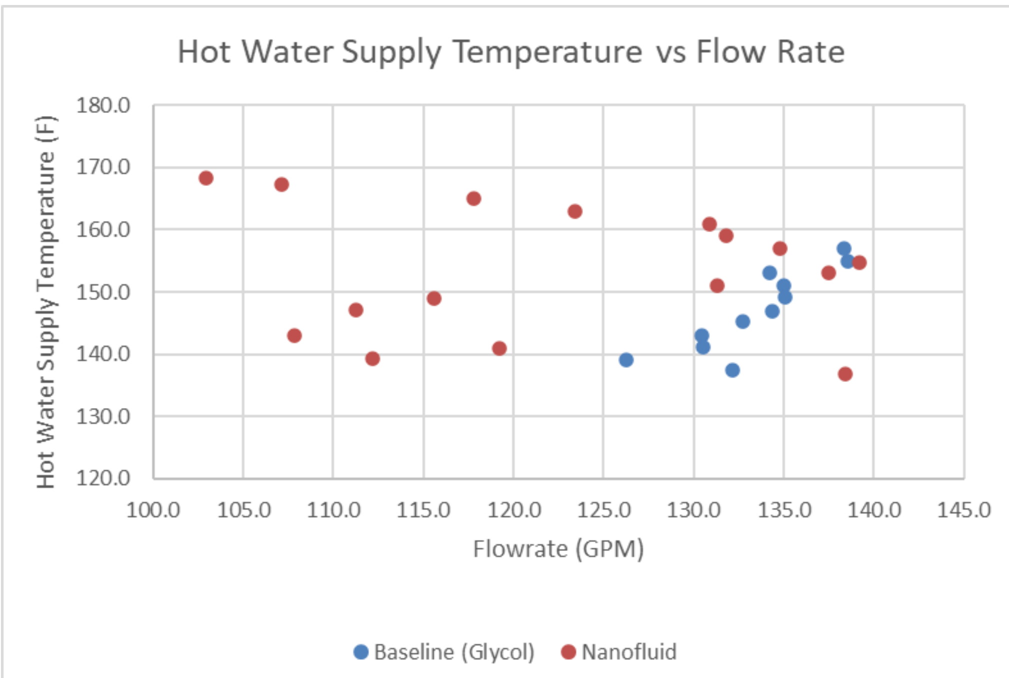
The project team did not attempt to normalize the operation of this system to typical annual weather conditions because the boiler loads do not correlate to ambient weather conditions. The boiler also serves a snowmelt system, a pool, and domestic hot water; no TRM methodology is available to apply to this system.

Discussion

While the heating system contains a series of high-efficiency condensing boilers, the calculated baseline efficiencies are higher than expected. The average estimated efficiency in the baseline condition (with glycol in multiple sub-loops) is approximately 96%. The boilers' full-load nameplate efficiency is approximately 94%.

The average efficiency across the entire operating range while using nanofluid is approximately 87%, much less than expected after nanofluid installation. Such a discrepancy in the tabulated efficiencies between the baseline and nanofluid collection periods points to the likelihood of changes to the system operating characteristics, inaccurate data measurements, or both.

Figure 24. Hot Water Supply Temperature Comparison



As shown in Figure 24, this boiler system supplied different water temperatures during the nanofluid data collection period (2022) compared to the baseline period (2021). The supplied water temperature was higher at some points in 2022; in other periods, the water temperature was lower. This discrepancy could be due to a faulty control valve found on December 1, 2021. Before the repair, the building maintenance staff placed the temperature controls in an override position to maintain the desired temperature. This operational change translated to a different hot water temperature than the originally designed operating sequence. It should be noted that the subsequent repair of this valve allowed for the resumption of the intended water temperature control sequence.

The difference in hot water temperatures may also stem from changes in the operating characteristics of systems tied to the sub-loops, such as the snow melt and pool. Unfortunately, available data limited the ability to investigate these potential impacts. The pool heating system was down for a period, which would have the effect of limiting the boiler load and possibly requiring lower-temperature water. But any other impacts on typical system operation are unknown.

The characteristics of this heating system lend themselves to an increased risk of discrepancies and inconsistent results. This system includes multiple subsystems with minimal data points tied to the digital automation system. These subsystems can impact the operation of the primary heating loop in multiple unforeseen ways. The relative complexity of the system increased the difficulty in determining observed discrepancies between monitoring periods. Finding simpler systems to study for field tests is an important finding of this study.

Site 5 – Residential Single-Family Boiler

A regression model of the home's natural gas usage was used to calculate the energy impacts of the nanofluid. Besides the boiler, other gas loads in the house include a clothes dryer used twice per week, a grill, and a garage heater used about twice per year. It was assumed that these loads would be roughly equal during the baseline and nanofluid monitoring periods.

Developing Energy Use Models

A linear least-squares regression model of the home's monthly gas usage compared to the heating degree days (HDD) for each month was developed to compare the natural gas usage of the facility before and after the installation of the nanofluid. Regressing the baseline data yielded the following equation:

$$Monthly\ Therms_i = 0.0845 * HDD_i + 23.617$$

Where:

HDDi = heating degree days for a month using a temperature balance point of 65°F. The balance point chosen for this home provided the best fit for the data.

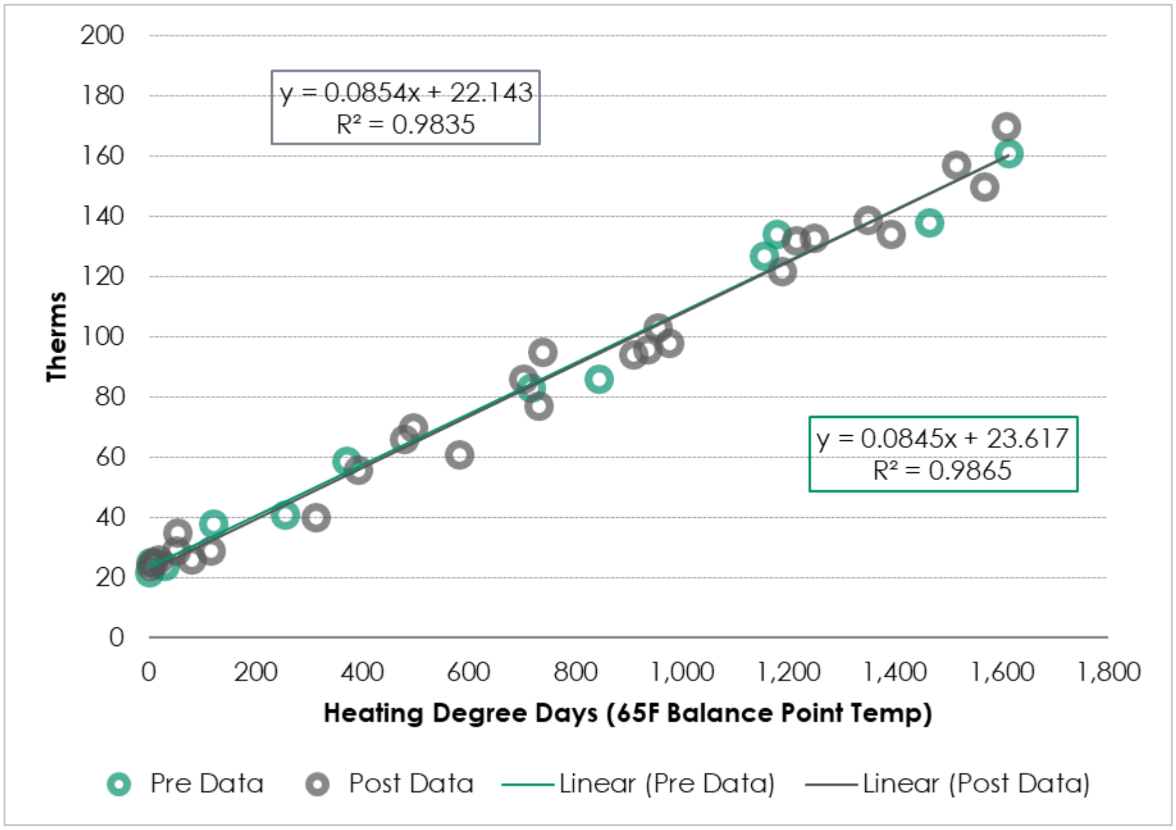
This equation yielded an R^2 value of 0.99 and a coefficient of variation of the root mean square error (CV RMSE) of 7.2%. These values indicate that this regression is an excellent fit for the data.

Regressing the nanofluid data yielded the following equation:

$$Monthly\ Therms_i = 0.0854 * HDD_i + 22.143$$

This equation yielded an R^2 value of 0.98 and a coefficient of variation of the root mean square error (CV RMSE) of 7.1%. As mentioned above, these values indicate a good-fitting model. These data sets and their regression models are plotted against the monthly heating degree days in Figure 25.

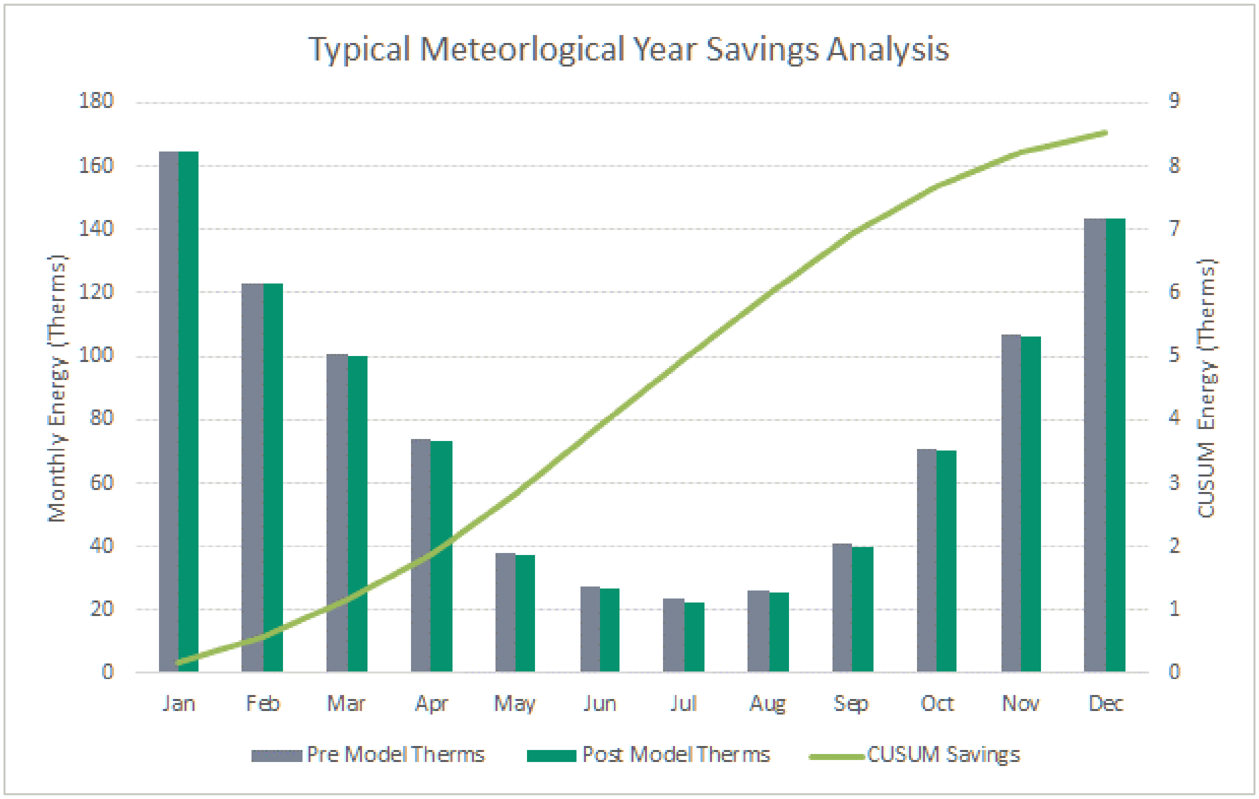
Figure 25. Regression Model Fits



Annual Savings Estimate

The linear regression models were applied to typical meteorological year (TMY3) weather data to normalize the analysis over the same annual weather period. Those results are shown in Figure 26. Weather normalized, the retrofit of nanofluids in this system shows a savings of nine Therms. Baseline Therm usage was modeled at 941 Therms annually for the household, which yields a savings of 0.9%.

Figure 26. Normalized Annual Savings



The incremental installation cost for 9.25 gallons of nanofluid at $67/gallon yields a cost of $619.75. The system saved nine Therms at $0.74 per Therm or $6.30 annually. The payback on the cost of the nanofluid based on these numbers is nearly 98 years, as shown in Table 19. The installation of the nanofluid saves approximately 99 lbs of carbon emissions per year, assuming an average natural gas emission rate of 116.5 lbs CO_2 per dekatherm of natural gas consumed.

Table 19. Normalized Savings

Data Point	Result
Water Therms	941
Nanofluid Therms	932
Therm Savings	9
Percent Savings	0.9%
Annual Carbon Savings (lbs)	99
Simple Payback (Years)	98.3

A fractional savings uncertainty analysis was also performed to determine the likely range of savings accounting for error in the regression models. That analysis indicated that this installation saved nine

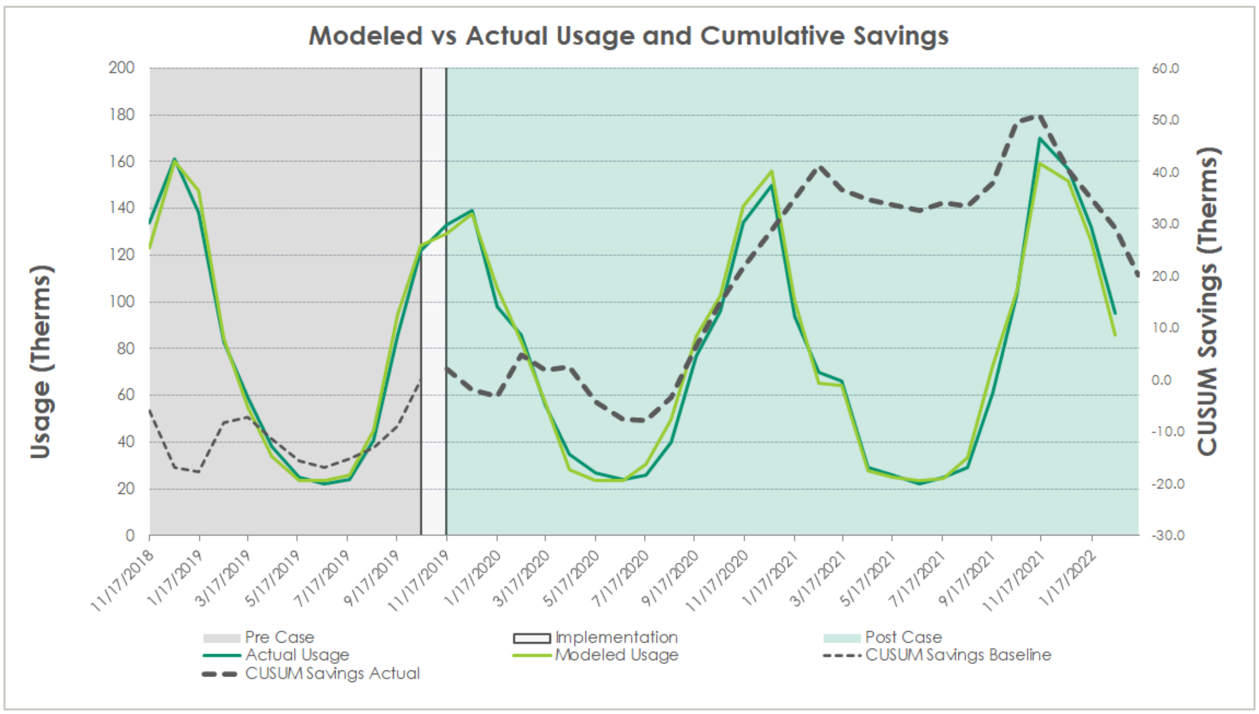
Therms plus or minus 18 Therms for a savings range of -9 to 27 Therms. Because a zero savings value is contained in the range, this analysis cannot statistically differentiate the savings from zero.

Discussion

The whole building regression model approach worked exceedingly well for the single-family residential building. As mentioned in the results section, the fit of the regression models was superb. Therefore, model fit is not a significant source of uncertainty in these results.

The cumulative sum of savings (CUSUM) is also plotted in Figure 27, showing the total energy savings over time. Over approximately two years of modeling, the analysis shows 20 Therms of energy savings. Looking at the CUSUM dotted line, it is apparent that most savings were accrued between August 2020 and March 2021. This finding implies that the heating was more efficient during winter than in the baseline model. Savings stopped accumulating during the summer of 2021. Savings again continued to accrue from October through December of 2021. However, after December 2021, the savings began to erode. The project team is unaware of any changes at the site and cannot explain this phenomenon.

Figure 27. Time Series Energy Use



System 6 – Residential Four-Plex Non-Condensing Boiler

A regression model of the building's natural gas usage was used to calculate the energy impacts of the nanofluid. Besides the boiler, other natural gas loads include a clothes dryer used approximately 46 times per month and a storage-type water heater. The project team assumes these loads are similar between the baseline and nanofluid monitoring period.

Developing Energy Use Models

A linear least-squares regression model of the building's monthly gas usage compared to the heating degree days (HDD) for the month was developed to compare the natural gas usage of the facility before and after the installation of the nanofluid. Regressing the baseline data yielded the following equation:

$$Monthly\ Therms_i = 0.2066 * HDD_i + 34.717$$

Where:

HDD_i = heating degree days for a month using a temperature balance point of 69°F. The selected balance point provided the best fit for the data.

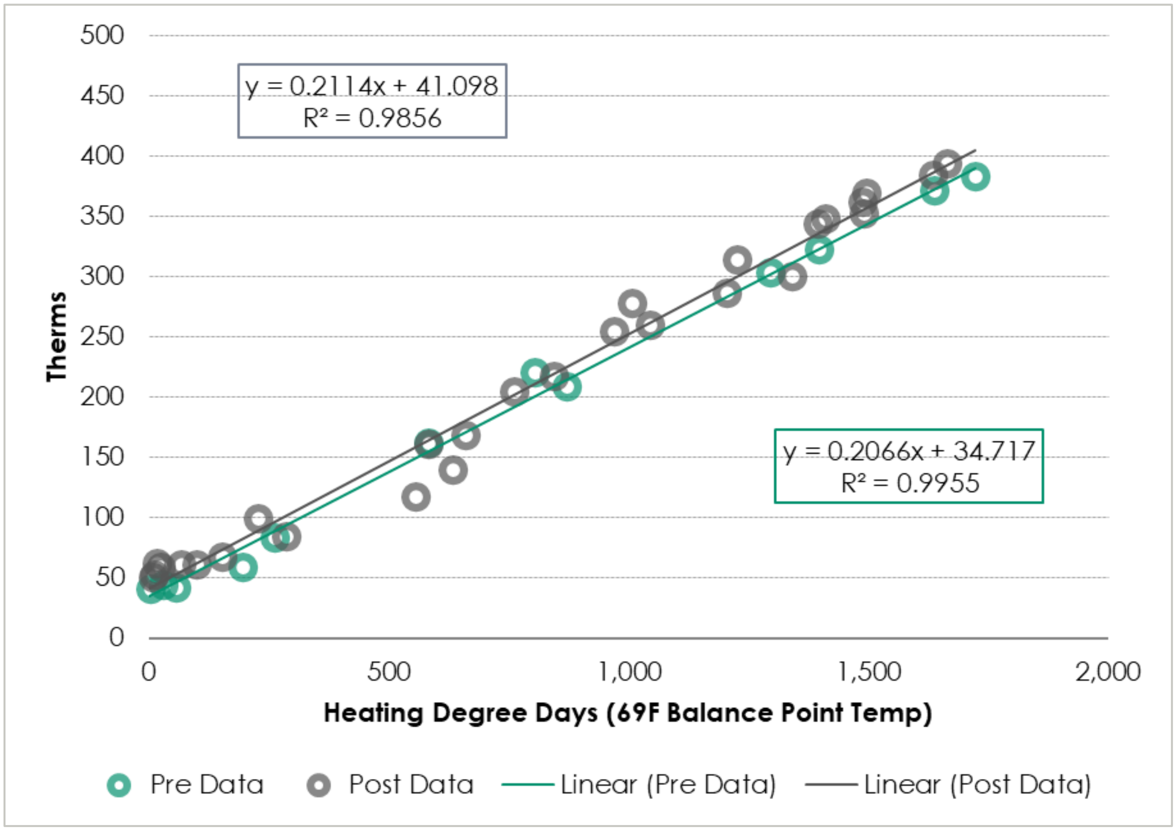
This equation yielded an R^2 value of 1.0 and a coefficient of variation of the root mean square error (CV RMSE) of 4.6%. Both of these values indicate a strong model fit.

Regressing the nanofluid data yielded the following equation:

$$Monthly\ Therms_i = 0.2114 * HDD_i + 41.098$$

This equation yielded an R^2 value of 0.99 and a CV RMSE of 7.0%. Once again, these metrics point to a good-fitting model. These data sets and their regression models are plotted against the monthly heating degree days in Figure 28.

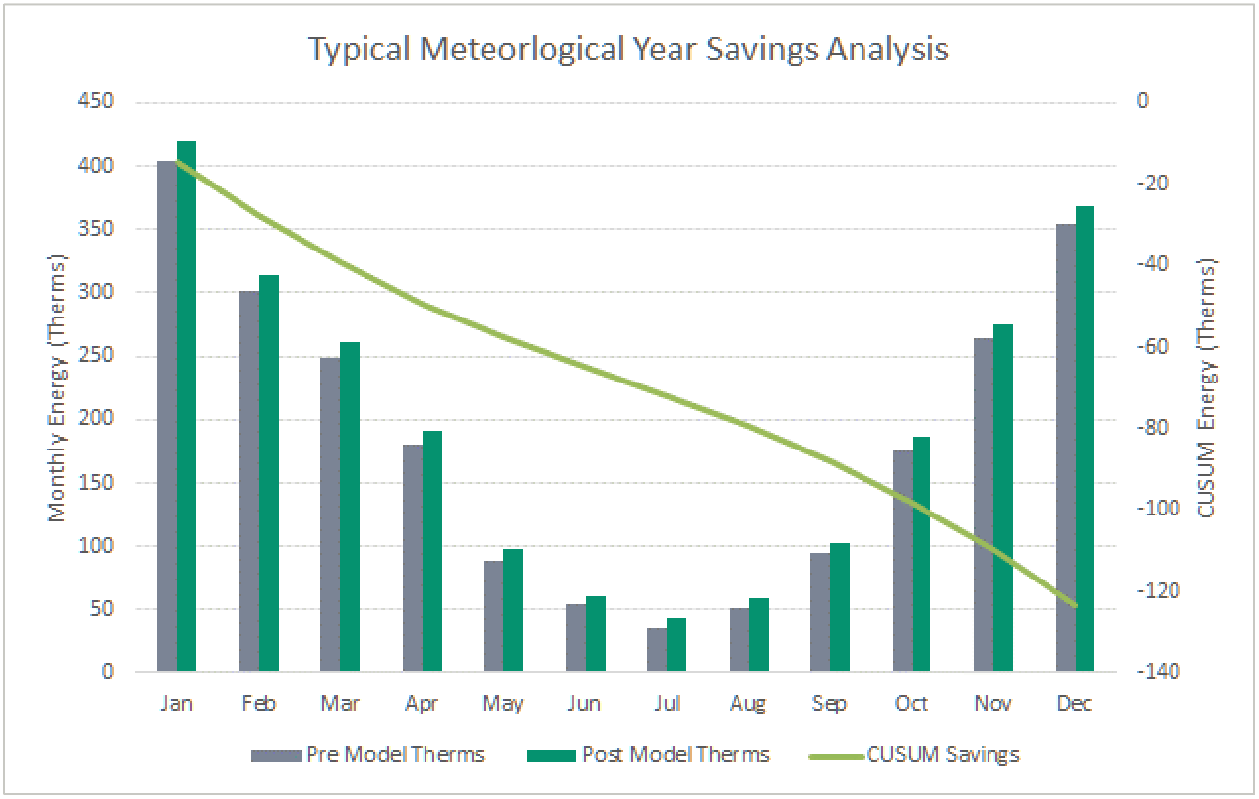
Figure 28. Regression Model Fits



Annual Savings Estimate

The linear regression models were applied to typical meteorological year (TMY3) weather data to normalize the analysis over the same annual weather period. Those results are shown in Figure 29. Weather normalized, the retrofit of nanofluids in this system shows an increase in gas usage of 124 Therms. Baseline Therm usage was modeled at 2,255 Therms annually for the building, which yields an increase in usage of 5.5%.

Figure 29. Normalized Annual Savings



The cost of the nanofluid for this installation was $804 based on a fluid cost of $67 per gallon and 12 gallons of nanofluid required to fill the system. This project does not have a payback period because this installation did not show savings. As shown in Table 20, based on the additional 124 therms of annual usage observed at this site, carbon emissions increased by 1,439 lbs, using an emission rate of 116.5 lb CO_2 per dekatherm.

Table 20. Normalized Savings

Data Point	Result
Water Therms	2,255
Nanofluid Therms	2,379
Therm Savings	-124
Percent Savings	-5.5%
Annual Carbon Savings (lbs)	-1,439
Simple Payback (Years)	N/A

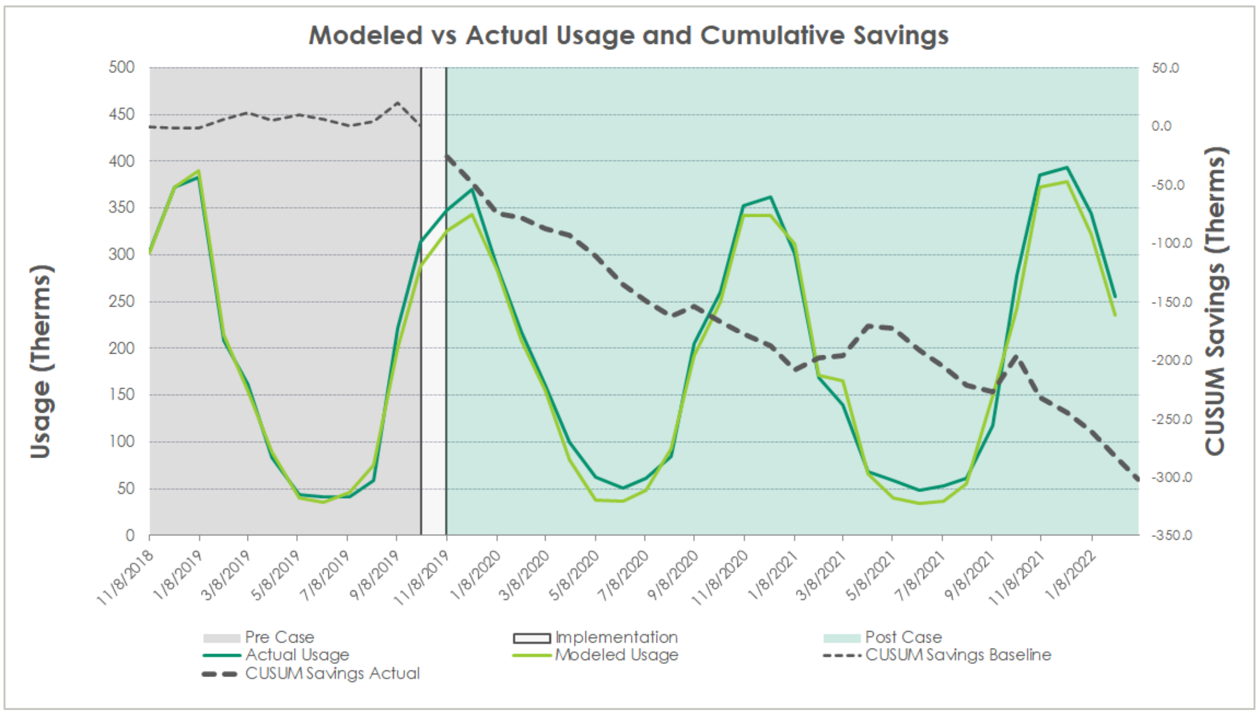
A fractional savings uncertainty analysis was also calculated to determine the likely range of savings accounting for error in the regression models. That analysis stated that the nanofluid monitoring period used an additional 124 Therms plus or minus 26 Therms, for an increased usage ranging from 98 Therms to 150 Therms. The fractional uncertainty analysis shows the entire range of energy impacts to use more energy than the baseline. Therefore, this site used more natural gas during the nanofluid monitoring period (not necessarily because of the nanofluid) than previously utilized.

Discussion

The whole building regression model approach was a good match for the residential four-plex building's behavior. As mentioned in the results section, the regression model provided a good fit. Therefore, model fit is unlikely to be a significant source of uncertainty in these results.

A time series plot showing the actual energy usage and the baseline regression usage can be seen in Figure 30. The cumulative sum of savings (CUSUM) is also plotted, showing the total energy savings over time. Over approximately two years of modeling, the analysis shows 302 Therms of additional gas usage. As seen in the CUSUM of savings dotted line, this site began using more natural gas immediately after the installation of the nanofluid. The energy use trended upward (negative savings) during the monitoring period after the nanofluid retrofit. The project team attempted to inquire with the owners and tenants about any impacts that could have led to this but could not identify any specific issues.

Figure 30. Time Series Energy Use



Energy Impacts Summary

The following table summarizes the impact of the nanofluid installation across each of the project sites. Table 21 shows that results vary across sites, from -22% savings to 29% savings, with no discernable pattern to the savings achieved. The savings achieved are based on metering during the COVID-19 pandemic, so they may reflect lower values than expected during a typical operation.

Table 21. Summary of Results

Site Name	System Type	Annual Energy Savings Estimate [c]	% Savings	Incremental Installation Cost	Operating Cost Reduction	Carbon Dioxide Reduction (lbs)	Simple Payback
Dakota County Administration	Water-Cooled Chiller	-6,927 kWh	-22%	$10,888	-$693	-3,380	N/A
Dakota County Administration	Air-Cooled Chiller	1,278 kWh	9%	$24,120	$128	624	188.7
Wooddale Dental	Non-Condensing Hot Water Boiler	426 Therms	29%	$7,035	$315	4,960	22.3
Courage Kenny	Condensing Hot Water Boiler	N/A	-14%	$7,404	-$1,752	-27,589	N/A
Residential Single Family	Condensing Boiler	9 Therms	1%	$619	$6	99	98.3
Residential Four-Plex	Non-Condensing Boiler	-124 Therms	-5%	$804	-$91	-1,439	N/A

c) Chiller systems denote kWh electric savings. Boiler systems denote the Therms of natural gas.

Commercial chiller and boiler systems showed savings and an increase in energy use, depending on the facility. The residential systems also showed savings and an increase in energy use. The study could not determine why some sites showed savings while others exhibited an increase in energy consumption.

The nanofluid installation had minor impacts on residential HVAC energy consumption compared to commercial systems. The project team is unsure why this occurred. It is possibly due to the analysis methodology differing between the residential and commercial system types. The regression modeling approach used for the residential sites may be inherently more conservative when calculating savings.

Residential facilities also have less variability in their operation. The residential regression analysis may more accurately reflect the actual energy impacts from nanofluid installation. If true, the more significant changes to energy consumption observed at the commercial sites may be partially due to variability in the operation of those sites. The project team cannot precisely determine why the residential findings differ from the commercial sites; these two points are merely hypotheses.

The payback period ranged from 22 to nearly 190 years for sites showing energy savings. The sites exhibited significant variations in the size of the HVAC system fluid loops. The payback period is highly correlated to the size of the loop, as larger loops require more gallons of nanofluid which directly increases the project cost.

Non-energy Impacts

While this study focuses heavily on the nanofluid technology's energy impacts, the installation's non-energy impacts were also assessed. The following sections summarize the non-energy impacts of the installation as described by the building owners and tenants through surveys. The surveys contained questions about potential changes to building comfort, maintenance needs, occupancy patterns, and heating and cooling control set points due to the nanofluid installation.

Appendix A: Occupant Survey contains a copy of the survey questions used for commercial and residential sites.

Commercial Findings Summary

None of the commercial buildings in the survey reported changes to their occupancy patterns during the data collection period. Despite this, the operating schedule of some equipment did end up changing. The chilled water equipment did not change its operating schedules. The air handler served by the boiler at Wooddale Dental changed its operation from 24 hours a day, seven days a week, to a 4 AM – 5 PM schedule, as stated in the Methodology section. The boiler at Courage Kenny did not change its operating schedule. However, the boilers did supply a higher maximum water temperature during the nanofluid data collection period due to a control valve repair that occurred shortly after the nanofluid installation.

Most sites saw no change in maintenance activity related to the systems after the nanofluid installation. One site replaced a failed water distribution pump, likely unrelated to the nanofluid installation.

No commercial sites reported a positive or negative change in building thermal comfort after nanofluid installation.

Residential Findings Summary

Neither of the residential sites reported a change in thermal comfort levels. None of the residential occupants reported changes to the equipment or building occupancy schedules.

Maintenance activities remained consistent at the four-plex with a non-condensing boiler system. The circulation pump in the single-family home with the condensing boiler system temporarily ceased operating after the nanofluid installation.

Freeze Protection

It should be noted that installing a nanofluid in all these systems provides additional freeze protection in many cases that did not exist previously. Freeze protection certainly provides some non-energy benefits that aren’t otherwise quantified in this study.

Analysis of Typical Installation Costs

Currently, retail costs for HYDROMX are around $67 per gallon per our discussions with the local manufacturer's representative. Systems are typically mixed at roughly 50% nanofluid base and 50% water, meaning a typical cost per gallon of loop volume would be $33.50.

Loop volumes for a water-sourced HVAC system vary widely depending upon the geometry of the building, the piping layout, and the number of hot water or chilled water coils. Determining an average size is difficult, but some industry recommendations are provided below.

Chiller manufacturing company York recommends that small-tonnage chillers for space cooling have a minimum loop volume of three gallons per ton. They state that the preferred volume is 5.0 to 8.0 gallons per ton (York by Johnson Controls n.d.). Other documents recommend 3-6 gallons per ton or 2-6 gallons per ton. Assuming a typical chiller loop size of three gallons per ton, the cost of the nanofluid would be approximately $100 per nominal ton of capacity. This cost does not include labor to replace or install the fluid in the loop.

The facilities in the study had volume-to-capacity ratios of 7.2 gallons per ton for the air-cooled chiller system and 1.25 gallons per ton for the water-cooled chiller system, for reference.

Finding a rule of thumb for heating systems proved to be more difficult. However, there is an equation widely used for estimating a minimum loop volume to prevent boiler short cycling.

$$V = \frac{T \times (QB - QL)}{\Delta T \times 60 \times 8.33}$$

Where:

V = volume of the hot water loop, gallons

T = minimum boiler firing time, typically 10 minutes, to prevent excess energy loss due to short cycling

QB = boiler output at minimum firing rate, BTU/hr

QL = minimum load of the system, BTU/hr

ΔT = design temperature difference of the system

Assuming that a 5:1 turndown ratio boiler with a 20-degree (°F) design temperature difference is typical, the equation would yield a volume of 20 gallons per 100,000 BTU/hr. This rule of thumb calculation would state that nanofluids cost roughly $670 per 100,000 BTU/hr of capacity.

The facilities in the study had volume-to-capacity ratios of 9.3 gallons per 100,000 BTU/hr for the single-family residence, 16 gallons per 100,000 BTU/hr for the four-plex, and 24.3 gallons per 100,000 BTU/hr for the commercial non-condensing boiler system, for reference.

Conclusions and Recommendations

CIP Recommendations and Impacts

Based on the variability seen in the results of this study, the project team does not believe there is enough evidence to support developing a prescriptive measure for the Minnesota TRM. Measures for the TRM need to exhibit repeatable savings, and the small number of test sites studied in this project does not meet that criterion.

However, based on the findings showing savings at several sites, the project team believes there is potential for savings using this technology. This technology would apply to CIP for all utility types in Minnesota as long as they have customers in their service territory that utilize water-source HVAC systems. Custom utility efficiency programs seem most suitable for nanofluids until more research and repeatable findings are available. The project team would suggest that custom rebates be contingent upon monitored results, as savings vary depending on the system type and other site-specific factors. The project team recommends that monitoring for custom rebates follow a similar process to that laid out in this report. Monitoring should include the input energy of the boiler or chiller and points necessary to quantify the heat supplied by a boiler or removed by a chiller. Until more research is done on using water-side heat transfer equations with nanofluids, alternative analysis approaches will be required. Examples of these approaches include using the HVAC system's air side or the chiller's condenser side.

Issues Encountered and Lessons Learned

Based on the variability of the savings observed at each test site, the project team deemed this study's findings inconclusive. The study was carried out using industry best practices to capture data with enough precision to pinpoint issues with the monitoring. However, the project team ran into several real-world issues that had to be dealt with, described below.

The Impacts of the COVID-19 Pandemic

The impacts of COVID-19 were undoubtedly felt during the monitoring portion of this study. The monitoring of the commercial sites was carried out from February 2020 to May 2022. Due to stay-at-home orders, many buildings were unoccupied for part or all of the test period. These orders led to two issues. First, some occupancy changes likely happened that the project team was unaware of during the study. Control sequence and occupancy schedule changes appear to have occurred based on the data collected from building automation systems. However, our contacts at these test facilities could not pinpoint specific changes made to the control system.

Second, many of these HVAC systems exhibited low loading conditions that would not reflect real-world operation during typical times. The study was designed to determine the efficiency of each system at various loads with and without using nanofluids. However, the efficiency and response of systems at the lower limits of their loading range can exhibit some odd behavior, which may be a factor in the results of this study. The project team was unaware of any feasible alterations to the study design that could have been utilized to account for the low-loading conditions of the HVAC equipment.

Data Quality Issues

This study encountered a few data quality issues that are worth mentioning. The Wooddale Dental site had a sensor that randomly stopped reporting the air volume of a variable air volume box. The Wooddale Dental site also contained a baseboard radiant hot water heating system that the project team was told was no longer functional. However, the radiant hot water panels were indeed operating. Data logging of the baseboard system was not set up in the building automation system. Therefore, it was impossible to quantify the nanofluid's impact on the baseboard system.

The project team intended to have real-time access to all the building automation systems to self-serve data from the system for our analysis needs and identify any issues early on. In practice, this proved difficult, as some facilities were unwilling to grant remote access to their building automation system. The project team had to rely on their staff to extract data for us as they had time. In other scenarios, extracting data from the building automation system was complicated and time-consuming. Having someone download the data regularly was unreasonable.

Had the project been able to set up easy-to-download data access to each site, some of these issues would have been identified earlier in the process. It may have been possible to install additional data logging equipment to capture a fuller picture of the monitored systems. More usable data points would have been available had issues been cleared up earlier in the process. Based on these findings, the project team recommends that any data logging studies for future CARD projects strive to retrieve data on an on-demand basis.

Recruiting Test Sites

While this study did not suffer from a lack of test sites, as it monitored more systems than initially planned, recruiting was challenging. It took much longer than anticipated to find test sites for this project. The project team believes this is because nanofluids are an emerging technology, and replacing the operating fluid within an HVAC system is a process that takes time. The project team spent over five times the amount of money initially budgeted on recruiting for this project and needed to request an extension of the project timeline. The project team encourages potential future researchers to consider the challenges associated with recruiting participants to test emerging technologies.

Future Research and Market Needs

The project team feels that the nanofluid technology is worth pursuing further based on some of the findings in this study and the theoretical research that laboratories have previously conducted. It is known that nanofluids can speed up heat transfer, but does the faster heat transfer lead to a reduction in energy usage in all cases? The project team hypothesizes that nanofluids can lead to energy savings. In particular where the increased heat transfer allows additional temperature resets or condensing boilers to operate longer in the condensing range. For this to occur, the building automation sequences may require changes to maximize the savings potential.

In addition to potential energy benefits, the nanofluid studied also offers freeze protection. Swapping from water to a standard water/glycol mixture typically would come with an energy penalty because of the reduced specific heat of the mixture. If utilizing a nanofluid even neutralizes that energy penalty, there is merit to using nanofluids as an energy savings measure.

The project team is planning follow-up testing efforts after the release of this report. Work is being done to resolve the foaming issue in the Dakota County water-cooled chiller. When complete, the project team plans on collecting additional data and revising the analysis for that site. The project team also intends to test another condensing boiler site. While a specific site has not been selected at the time of this writing, the recruiting effort will target a more straightforward system serving only HVAC loads.

However, to accurately determine the savings associated with using nanofluids in HVAC applications, with minimal room for interpretation, the project team suggests that the nanofluid products be tested in a controlled laboratory environment. Organizations like the Lawrence Berkley National Laboratory may be able to test boiler and chiller systems using nanofluids for heat transfer. These tests could precisely control each variable and determine which conditions nanofluids lead to energy savings.

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Appendix A: Occupant Survey

Commercial Survey:

Q1) What is the temperature set point on your thermostats (please indicate overnight temperature setbacks, if applicable)? Have you changed any thermostat temperature set points since the nanofluid was installed? If yes: Please specify what changes were made.

Q2) Have you changed any other HVAC control or operating sequences (e.g., hot water/chilled water temperature set points or resets) since the nanofluid was installed? If yes: Please specify what changes were made.

Q3) Have there been any other facility changes (e.g., new heating or cooling equipment, changes in occupancy patterns, space use, or schedules due to COVID-19) since the installation of the nanofluid that may have impacted the energy consumption of the facility as a whole? If yes: Please describe the changes.

Q4) Since the nanofluid was installed, have you noticed any changes in the comfort level of your facility in terms of temperature? If yes, would you say that, because of the nanofluid installation, your facility is MORE comfortable than before the improvements were made, LESS comfortable, or would you say there is no difference in the comfort level?

Q5) In terms of the maintenance requirements of your heating/cooling equipment, would you say that because of the installation of the nanofluid, your heating/cooling equipment 1) requires LESS maintenance than before the improvements were made, 2) requires MORE maintenance, or would you say that 3) there is no difference in the maintenance requirements of your heating/cooling equipment?

Table 22. Commercial Occupant Survey Results

Question	Dakota County	Wooddale Dental	Courage Kenny
Q1	*Cooling Set Point – 75°F (Day); 77°F at night* *Heating Set Point – between 67°F and 72°F (Day); 70°F (Night)*	*Cooling Set Point – 70-72°F (Day); 80°F at night* *Heating Set Point – between 67°F and 72°F (Day); 65°F (Night)*	*During occupied hours, most of the VAVs are set at 72-74°F.* *Unoccupied setpoints are 65°F for heat and 80°F for cooling.* *No significant changes have been made. Although each VAV zone can be adjusted from the space, unoccupied setpoints are not changeable from the user end in the space.*
Q2	*No Changes*	*N/A*	*No changes made*
Q3	*Spaces are approximately 50% occupied due to COVID-19*	*N/A*	*No changes made*
Q4	*No Changes*	*No Changes in comfort level*	*None noted, as the setpoints have stayed the same.*
Q5	*Everything has remained the same*	*(Mechanical Contractor) has spent more time here than in the past*	*No noticeable pros or cons. The nanofluid hasn't been in that long yet.*

Residential Survey:

Q1) Since November 2019, have you kept your heating the same as the previous winter? Have you turned up the heat compared to the previous winter? Turned down the heat compared to the previous winter?

Q2) Has anything changed in your home since November 2019? For example: Are more or fewer people living in your house? Are people at home more or less often? Did you purchase a new television, room heater, or other product that plugs into the wall? Have there been other changes to your home or schedule because of COVID-19? Have there been any other changes?

Q3) Since November of 2019, has the temperature in your home been more comfortable, less comfortable, or no different?

Q4) In terms of the maintenance requirements of your heating equipment, would you say that because of the installation of the nanofluid, your heating equipment 1) requires LESS maintenance than before the improvements were made, 2) requires MORE maintenance, or would you say that 3) there is no difference in the maintenance requirements of your heating equipment?

Table 23. Residential Occupant Survey Results

Question	Single Family	Four-Plex
Q1	*Heating 73°F 24/7 This has been our set point for the last 4-5 years.*	*Yes, we did (keep constant temperature set points), we didn't make any changes, and we use it as much as last year*
Q2	*No*	*No, we are still the same people living here and didn't buy anything for the house and stay home most of the time, even if it wasn't COVID-19*
Q3	*No change*	*More comfortable – we don't need to turn the heater on all day and night – just a little to get warm*
Q4	*The boiler circulating pump stopped working in February 2020. Did heavy water cause this?*	*Heating system maintenance is the same as in the past. Once a year, the boiler gets an inspection and cleaning. There has been no extra effort made.*

Appendix B: Analysis Methodology

Site 1 - Dakota County Water-Cooled Chiller

Equipment Details

Table 24 shows the specifications of the primary system components.

Table 24. Site One Equipment

Equipment	Type	Qty	Size	Units
Chiller	Rotary Screw	1	255	Ton
Chilled Water Pumps - Primary	Centrifugal	2	15	HP
Cooling Tower	Forced Draft	2	10	HP
Condenser (Tower) Pumps	Centrifugal	2	15	HP

Data Collection

For this test site, data were collected on the condenser side of the chiller. This approach avoided attempting to calculate the heat transfer of the nanofluid on the chiller side since the specific heat of that mixture is unknown. The manufacturer claims that heat transfer cannot be calculated for nanofluids using standard heat transfer equations.

The chilled water load can be calculated using the condenser water load and deducting the heat of rejection from the chiller compressor. The condenser water load was calculated using the condenser system flow and temperature differential (supply and return). Table 25 lists the data points collected from the facility’s digital automation system and their collection interval.

Table 25. Water-Cooled Chiller Collected Data Points

BAS Data Point	Units	Collection Interval (Min)
Outdoor Air Dry Bulb Temperature	°F	5
Outdoor Air Wet Bulb Temperature	°F	60
Chiller Compressor Current (3 Phases)	Amps	5

BAS Data Point	Units	Collection Interval (Min)
Chiller Compressor Voltage	Volts	5
Condenser Water Flow Rate	Gallons per Minute	5
Condenser Supply Temperature	°F	5
Condenser Return Temperature	°F	5

Baseline Period

The chilled water system utilized city water for the evaporator and condenser loops in the baseline condition. The baseline monitoring period occurred from August 1, 2020, to October 29, 2020.

Besides the outdoor wet-bulb temperature, data was collected from the building automation system in five-minute increments to capture system performance. Relevant data points were averaged based on outdoor air temperature bins of two degrees Fahrenheit to process the large amounts of data into identifiable trends.

The baseline data collection period captured over 2,500 data points encompassing roughly 200 hours of chiller operation. Since the data collection began in August, the baseline data set did not contain operating data where outdoor air temperatures exceeded 87°F.

Nanofluid Period

The fluid on the system's evaporator side was replaced on April 13, 2021, with a mixture of 45% HYDROMX and 55% city water. The total loop volume of the chiller system was found to be 325 gallons during replacement. The system was monitored from August 1, 2021, to October 14, 2021. Note that this is a shorter period of data collection than anticipated. After installation of the nanofluid, the system was experiencing excessive foaming and was causing system alarms. The foaming and air pocket found in the system following nanofluid installation prompted the installation of a relief valve. The valve was not installed until later in the summer. Data collection resumed after the installation of the valve.

The nanofluid data collection period captured over 1,800 data points over the cooling season, equating to roughly 150 hours of chiller operation.

Analysis Procedure

Determining the system's efficiency (kW/ton) requires two separate calculations from the metered data.

The power consumption of the chiller (kW) is calculated using the following formula:

$$kW_{Chiller} = \frac{Average(Current_A,\ Current_B, Current_C) * Voltage * PF}{1{,}000\ \frac{watts}{kW}}$$

Where:

$Current_{A,B,C}$ = Compressor current of each of the three legs, obtained from the building automation system, (amps)

Voltage = electric potential of the compressor, obtained from the building automation system

PF = Power Factor, (0.78 assumed)

The tons of cooling delivered to the building were determined using measurements on the condenser water side. This fluid acted as the control variable for this analysis. Therefore, the removed energy correlated directly to the power consumption of the chiller.

$$Tons = \frac{500 * GPM * (T_{CWR} - T_{CWS}) - (kW_{Chiller} * 3413)}{12{,}000}$$

Where:

500 is the calculation coefficient, derived from 8.34 lb_{water}/gallon * 60 minutes/hr * 1 BTU / lb_{water} - °F

GPM = flow rate of the condenser water loop in gallons per minute, obtained from the building automation system

$T_{\_CWR}$ = measured condenser water temperature leaving the chiller, obtained from the building automation system (°F)

$T_{\_CWS}$ = measured condenser water temperature entering the chiller after it has passed through the cooling tower, obtained from the building automation system (°F)

3413 = conversion factor to BTU/hr. One kW of power = 3,413 BTU/hr of heat

12,000 = conversion factor to tons. One ton of cooling = 12,000 BTU/hr of heat transfer

Site 2 - Dakota County Air-Cooled Chiller

Equipment Details

Table 26 shows the specifications of the primary system components.

Table 26. Air-Cooled Chiller Equipment Specifications

Equipment	Type	Qty	Size	Units
Chiller	Screw	1	100	Ton
Chilled Water Pumps	Centrifugal	2	7.5	HP
Air Handler - Supply Fan	Centrifugal	1	50	HP

Equipment	Type	Qty	Size	Units
Air Handler - Return Fan	Centrifugal	1	15	HP

Data Collection

The air handler is the only end-use served by the chilled water loop. Therefore, the load on the air handler chilled water coil was utilized to determine the load on the chiller. Table 27 lists the data collected from the facility's digital automation system.

Table 27. Air-Cooled Chiller Data Points

BAS Data Point	Units	Collection Interval (Min)
Outdoor Air Dry Bulb Temperature	Deg F	5
Outdoor Air Wet Bulb Temperature	Deg F	60
Outdoor Air Humidity	%	60
Air Handler Outdoor Air Volume	CFM	5
Chiller Power	kW	3
Chiller Evaporator Flow Rate	Gallons per Minute	3
Chilled Water Supply Temperature	Deg F	3
Chilled Water Return Temperature	Deg F	3
Air Handler Return Air Humidity	%	5
Air Handler Return Air Volume	CFM	5
Air Handler Mixed Air Temperature	Deg F	5
Air Handler Supply Air Temperature	Deg F	5

BAS Data Point	Units	Collection Interval (Min)
Air Handler Supply Volume	Cubic Feet Per Minute	5
Air Handler Supply Fan Speed	Percent	5
Cooling Valve Position	Percent Open	5

Baseline Period

The chiller system utilized a glycol/water mixture as the heat transfer medium in the baseline condition. The mixture contained approximately 30% glycol, providing freeze protection at 7°F outdoor air temperature. The baseline monitoring period occurred from August 12, 2020, to October 30, 2020.

Data was collected from the building automation system in five-minute increments to capture system performance. Relevant data points were averaged based on outdoor air temperature bins of three degrees Fahrenheit to process the large amounts of data into identifiable trends.

The baseline data collection period captured over 3,300 data points encompassing roughly 275 hours of chiller operation. Since the test began in mid-August, the baseline monitoring period did not contain operating data where outdoor air temperatures exceeded 87°F.

Nanofluid Period

The fluid in the chiller system was replaced on April 13, 2021, with a mixture of 45% HYDROMX and 55% city water. The total loop volume of the chiller system was found to be 720 gallons. The air-cooled chiller system was monitored from May 3, 2021, to October 14, 2021.

The nanofluid data metering captured over 12,600 data points over the entire cooling season, equating to roughly 1,050 hours of chiller operation.

Analysis Procedure

The tons of cooling delivered to the airstream were determined using the following equation:

$$Tons = \frac{4.5 * CFM * (h_{Mixed\ air} - h_{Supply\ air})}{12{,}000\ BTU/ton}$$

Where:

4.5 is the calculation coefficient, derived from 0.075 lbs/ft^3 * 60 minutes/hr, where 0.075 lbs/ft^3 is the density of air at standard conditions at sea level

CFM = airflow across the chilled water coil in cubic feet per minute, obtained from the building automation system

$h_{mixed\ air}$ = calculated enthalpy of the mixed air entering the cooling coil, BTU/lb

$h_{supply\ air}$ = calculated enthalpy of the supply air leaving the cooling coil, BTU/lb

12,000 is the conversion factor to tons. One ton of cooling = 12,000 BTU/hr of heat transfer

The enthalpy of the mixed and supply air streams was calculated using the following equation from the ASHRAE Fundamentals Handbook (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2021).

$$h = 0.24 * T + w * (1061 + 0.444 * T)$$

Where:

h = enthalpy of the air stream, BTU/lb

T = temperature of the airstream, °F

w = humidity ratio of the airstream, lb water/lb dry air

The supply air enthalpy is calculated using the supply air temperature from the building automation system and the supply air humidity ratio. The supply air humidity ratio must be calculated because the building automation system does not monitor that parameter.

When humid air is cooled across a cooling coil, the air approaches a saturated humidity state. This analysis assumes that humid air leaves the cooling coil at approximately 95% relative humidity. Suppose the air entering the coil is dry and contains less humidity than saturated air at the coil temperature. In that case, the coil achieves sensible cooling only, and no humidity is removed from the airstream. In that case, the humidity ratio of the air does not change in the cooling process. For this analysis, the supply air humidity is set as the lesser of the humidity ratio at the supply air temperature and 95% relative humidity or the humidity ratio of the mixed air entering the cooling coil.

The building automation system does not collect air handler mixed air humidity ratio values. Therefore, the mixed air humidity ratio was calculated using outdoor air and return air humidity ratio values as shown in the following equation:

$$w_{mixed\ air} = w_{return\ air} * \left(1 - \frac{CFM_{outdoor\ air}}{CFM_{supply\ air}}\right) + w_{outdoor\ air} * \frac{CFM_{outdoor\ air}}{CFM_{supply\ air}}$$

The mixed air enthalpy was calculated using the mixed air temperature from the building automation system, and the mixed air humidity ratio was calculated using the above equation.

Alternate Water Side Analysis

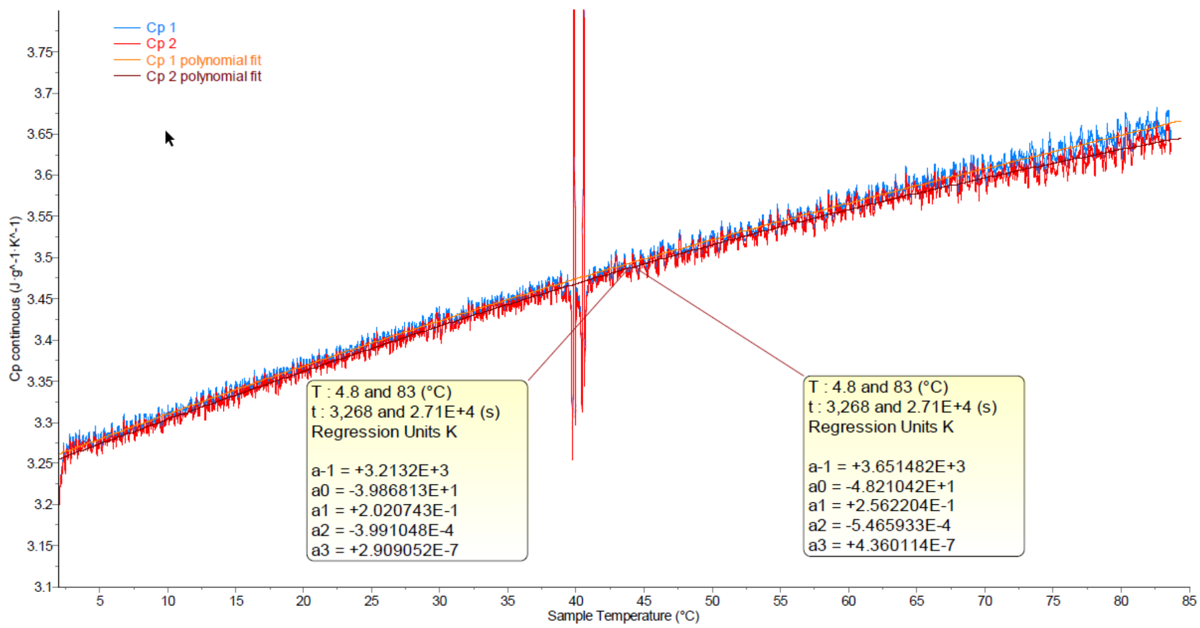
During a third-party review process, it was recommended that the project team look at the water side of this system to determine the efficiency impacts of using the HYDROMX nanofluid. This approach was not part of our original research plan, as the manufacturer states that a typical specific heat analysis does not accurately quantify heat transfer. The following quote is located on the frequently asked questions portion of their website:

"While this is a common engineering question, it is also a misapplied question for nanofluids. Specific heat is measured with the fluid static. HVAC systems operate with the fluid in motion and, better yet, the fluid in turbulence. Nanofluids outperform other fluids when in turbulence.

Also, some nanofluids (including HYDROMX) are non-Newtonian, which means their characteristics change under stress. HYDROMX is a sheer-thinning nanofluid where its fluid pressure drop improves as it is placed under stress." (HYDROMX 2022)

One of the challenges in conducting a water-side energy analysis is locating the specific heat of the product, as HYDROMX does not publish this information. The project team located a laboratory test specifying the specific heat of the HYDROMX product (Setaram Instrumentation 2016). Figure 31 shows the specific heat of a 100% HYDROMX solution at various temperatures.

Figure 31. HYDROMX Specific Heat



Unfortunately, the chart does not provide a specific heat of a 50% HYDROMX mixture. An analysis was done to calculate the specific heat at a 50% water and 50% HYDROMX mixed solution. At 45°F, the specific heat of a 50% HYDROMX solution is stated to be almost 0.902 BTU/lb°F. The specific heat is similar to that of a standard glycol mixture and about 90% of pure water. The density of a 50% HYDROMX fluid was also found in a separate test report (Laboratory of Thermophysical Properties & Environmental Processes 2013).

Figure 32. HYDROMX Density Table

Table 1.1. Measurements of the Density as a function of temperature.

Temperature ('C)	Temperature (K)	Density ($kg\ m^{-3}$) measured	Density ($kg\ m^{-3}$) fitted	Deviations (%)
-17.30	255.85	1088.5	1089.1	-0.06
3.20	276.35	1078.3	1076.7	0.14
11.00	284.15	1071.3	1072.0	-0.07
14.40	287.55	1070.2	1070.0	0.02
18.40	291.55	1067.4	1067.6	-0.02
30.40	303.55	1061.1	1060.4	0.07
42.60	315.75	1053.4	1053.0	0.04
53.90	327.05	1046.7	1046.2	0.05
62.70	335.85	1040.8	1040.9	-0.01
71.30	344.45	1035.1	1035.7	-0.06
79.80	352.95	1030.5	1030.6	-0.01

Site 3 - Wooddale Dental Non-Condensing Boiler

Equipment Details

Table 28 shows the specifications of the primary system components.

Table 28. Site Three Equipment

Equipment	Type	Qty	Size	Units
Hot Water Boiler	Non-Condensing	1	600	MBH
Boiler Pumps 1, 2	Inline	2	0.75	HP
Air Handler Supply Fan	Variable Volume	1	8,200 [d]	CFM

d) Approximate

Data Collection

The boiler load was calculated using the total air-side heating load of the VAV boxes. This approach was used to avoid calculating the nanofluid's water-side heat transfer, as the manufacturer states that it is impossible with standard heat transfer equations. Table 29 lists the data collected from the facility's digital automation system.

Table 29. Collected Data Points

BAS Data Point	Units	Collection Interval (Min)
Air Handler Supply Speed	Hz	5
Air Handler Supply Air Temperature	°F	3
VAV Terminal Airflow	CFM	5
VAV Terminal Discharge Air Temperature [e]	°F	5
Hot Water Pump 1, 2 Current	Amp	5
Hot Water Loop, Supply Temperature	°F	5
Hot Water Loop, Return Temperature	°F	5
Hot Water Loop, Flowrate	GPM	5
Gas Volume	Cubic Ft	60
Cooling Stage 1, 2 Status	On/Off	5

e) VAV Boxes 1-14

Baseline Period

The heating loop used water as the working fluid in the baseline condition. The baseline data collection period spanned from January 1, 2021, to May 1, 2021. The BAS was accessed remotely regularly to collect the most recent data. The data were averaged based on outdoor air temperature bins of four degrees Fahrenheit to process the data into identifiable trends. The nanofluid data collection period captured 869 hourly data points over the early 2021 heating season.

Nanofluid Period

The water in the heating loop was replaced on November 30, 2021. After replacement, the final fluid ratio in the system was 51% HYDROMX and 49% city water, with a total loop volume of 105 gallons. The nanofluid data monitoring period spanned from January 1, 2022, to April 26, 2022. The data were averaged based on outdoor air temperature bins of four degrees Fahrenheit to process the data into identifiable trends. The nanofluid data collection period captured almost 900 hourly data points over the early 2022 heating season.

The project team noticed that the boiler operating schedule changed during the nanofluid metering period. Sometime after the installation of the nanofluid, the control sequence was changed to only allow the boilers to run during the occupied schedule of 4 AM – 5 PM on weekdays. During the baseline monitoring period, the boilers operated outside this scheduled window. The project team decided to only analyze the efficiency of the boilers during the weekday 4 AM – 5 PM occupied window over the entire monitoring period to provide an equal comparison of operation.

Analysis Procedure

This energy analysis calculates thermal efficiency, which is the ratio of the natural gas consumption of the boiler (Energy Input) to the heat delivered to each VAV box (Energy Output):

$$Thermal\ Efficiency, \% = \frac{Energy\ Output, \frac{BTU}{hr}}{Energy\ Input, \frac{BTU}{hr}}$$

The energy input was estimated using an assumed rate of 1,015 BTU of energy per cubic foot of gas[1] reported by the building automation system.

The heat energy delivered to the VAV air streams was calculated using the following equation:

$$Energy\ Output, \frac{BTU}{hr} = \sum_{i=1}^{13} 1.08 * VAV_{i,CFM} * \left(T_{AHU\ Discharge} - T_{VAVi,Supply}\right)$$

Where:

1.08 is the calculation coefficient, derived from 0.075 lb_{air}/cubic foot * 60 minutes/hr * 0.24 BTU / lb_{air} - °F

$VAV_{i,CFM}$ = air volume across the VAV reheat coil, obtained from the building automation system (cubic feet per minute)

$T_{AHU\ Discharge}$= air temperature after it leaves the central air handler, but before it reaches the VAV reheat coil, obtained from the building automation system (°F)

$T_{VAVi,Supply}$= air temperature after it is heated by the reheat coils, obtained from the building automation system (°F)

[1] "Fuel Gas." McGraw Hill Encyclopedia of Science & Technology. McGraw Hill, Inc., 1982. https://hypertextbook.com/facts/2002/JanyTran.shtml

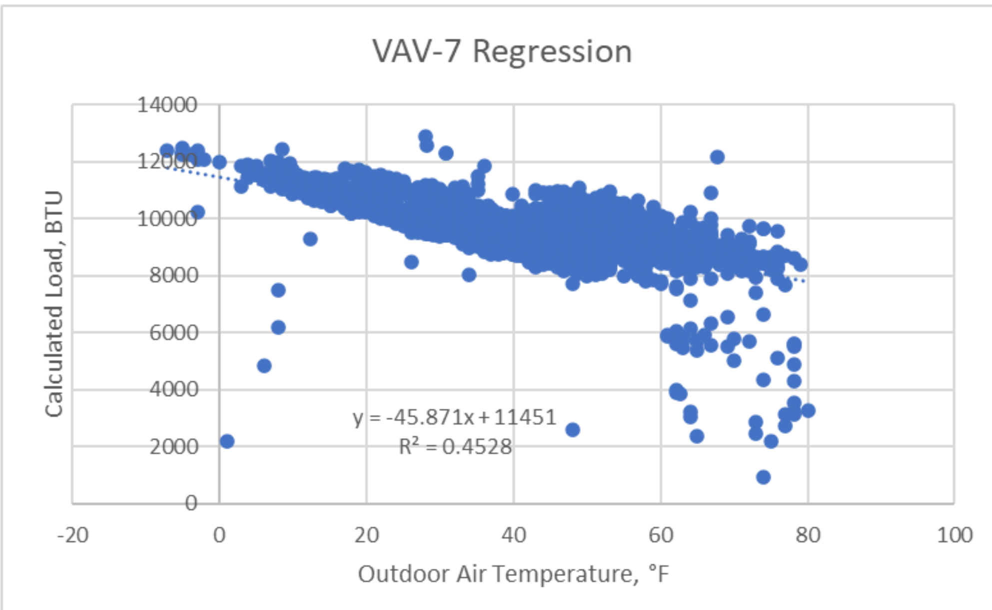
The air volume data was unavailable for one of the VAV terminals for the entire monitoring period due to a BAS malfunction (VAV-7). Therefore, the loads during the malfunctioning period were calculated using a regression between the calculated load on the reheat coils while the BAS reported values and outdoor air temperature. The regression relationship was used to estimate the load values to fill in the missing data.

Regressing the baseline data yielded the following equation:

$$Heating\ Load, BTU = -45.871 * Outdoor\ Air\ Temperature\ (°F) + 11{,}451$$

This equation yielded an R^2 value of 0.458, as shown in Figure 33.

Figure 33. Regression of VAV-7 Load vs. Outdoor Air Temperature



Site 4 - Courage Kenny Condensing Boiler System

The building heating system includes a primary hot water distribution loop fed by a series of modular condensing boilers. Each boiler contains a dedicated fixed-speed circulation pump that feeds water from the primary loop through the boilers. Variable speed pumps distribute hot water throughout the primary loop, supplying terminal reheat coils, fin tube radiation, and four sub-loops.

Each heating sub-loop receives heat from one or more plate-and-frame heat exchangers. Two-way water valves on the boiler side of the heat exchangers modulate the hot water flow to maintain the temperature set points of the sub-loops.

The sub-loops provide heating for the therapy pool, the air handler heating coils, the sidewalk snowmelt system, and the facility's domestic hot water system.

Equipment Details

Table 30 shows the specifications of the primary system components.

Table 30. Equipment Specifications

Equipment	Type	Qty	Size	Units
Hot Water Boiler	Condensing	3	500	MBH
Hot Water Boiler	Condensing	1	941	MBH
Boiler Circulation Pumps	Inline	3	0.5	HP
Distribution Pumps, HWP1 & HWP2	Centrifugal	2	5	HP

Data Collection

The boiler load was calculated using the flow rate and temperatures of the primary water loop. The facility's digital building automation system (BAS) reported most of the required data points in five-minute increments. The BAS data were averaged based on hot water supply temperature bins to process the data into identifiable trends.

Table 31 lists the data collected from the facility's digital automation system.

Table 31. Condensing Hot Water Data Points

BAS Data Point	Units	Collection Interval (Min)
Outdoor Air Dry Bulb Temperature	°F	5
Total Gas Usage	CCF	1
Boiler Pump 1, 2 Speed	Hz	5
Boiler Pump 1,2 Current	Amp	5

BAS Data Point	Units	Collection Interval (Min)
Boiler Pump 1, 2 Power	Watt	1
Boiler 1, 2, 3 Firing Rate	%	5
Boiler 1, 2, 3 Pump Status	On / Off	1
Boiler 1, 2, 3 Gas Valve Position	Open / Closed	1
Sync Boiler 1, 2 Pump Status	On / Off	1
Sync Boiler 1, 2 Firing Rate	%	5
Sync Boiler 1, 2 Gas Valve Position	Open / Closed	1
Main Loop Hot Water Flow	GPM	1
Hot Water Supply Temperature	°F	5
Hot Water Return Temperature	°F	5
Hot Water Supply Temperature Set Point	°F	5
AHU Loop Pump P4, P5 - Speed	Hz	5
AHU Loop Pump P4, P5 - Current	Amp	1
AHU Loop Pump P4, P5 - Power	kW	1

BAS Data Point	Units	Collection Interval (Min)
AHU Loop Supply Water Temperature	°F	5
AHU Loop Return Water Temperature	°F	5
AHU Loop HX Valve Command	%	5
Snow Melt Pump 7 Status	On / Off	5
Snow Melt Supply Water Temperature	°F	5
Snow Melt Return Water Temperature	°F	5
Snow Melt HX Valve Command	%	5

Baseline Period

The snow-melt loop contained approximately 41% glycol, and the air handler loop contained 32% glycol in the baseline condition.

A third party with access to the building automation system collected the baseline data. The baseline monitoring period occurred between January 1, 2021, and May 1, 2021.

Nanofluid Period

The glycol in the snowmelt and air handler sub-loops was replaced on December 1, 2021. The total volume of both loops was 110.5 gallons. The fluid ratio in the snow melt system was 47% HYDROMX and 53% city water, and the air handler loop was 36% HYDROMX and 64% city water.

The complete baseline data was collected by a third party with access to the building automation system and included data for January 1, 2022 through May 2, 2022. The data monitoring period for the HYDROMX operation occurred between January 1, 2022, and May 1, 2022.

Analysis Procedure

The system's energy analysis involves the calculation of thermal efficiency, which compares the energy consumption of the boilers to the heat energy delivered to the central heating loop:

$$Thermal\ Efficiency, \% = \frac{\text{Energy Output}, \frac{\text{BTU}}{\text{hr}}}{\text{Energy Input}, \frac{\text{BTU}}{\text{hr}}}$$

The energy input was estimated using an assumed rate of 1,015 BTU of energy per cubic foot of natural gas.[2]

The heat energy delivered to the central loop is derived using the following equation:

$$Energy\ Output, BTU/hr = 500 * GPM * (T\_Supply - T\_Return)$$

Where:

500 is the calculation coefficient, derived from 8.34 lb_{water}/gallon * 60 minutes/hr * 1 BTU / lb_{water} - °F

GPM = water flow through the central hot water loop in gallons per minute, obtained from the building automation system

T_Supply = measured water temperature after it is heated by the boilers, obtained from the building automation system (°F)

T_Return = measured water temperature after it returns from the building, obtained from the building automation system (°F)

Water temperatures were collected from the building automation system directly. The water flowrate data (GPM) was unavailable for the entire nanofluid monitoring period due to a malfunction of the flowmeter. Therefore, the GPM data point was calculated using a regression model with the measured speed of the central loop circulation pump motors (P1 and P2) from 2021. The 2021 regression relationship was used to compile the GPM values for 2022.

Regressing the baseline data yielded the following equation:

$$Gallons\ per\ Minute, GPM = 15.128 * Pump\ Speed\ (°Hz) - 567.07$$

This equation yielded an R^2 value of 0.6382, as shown in Figure 34.

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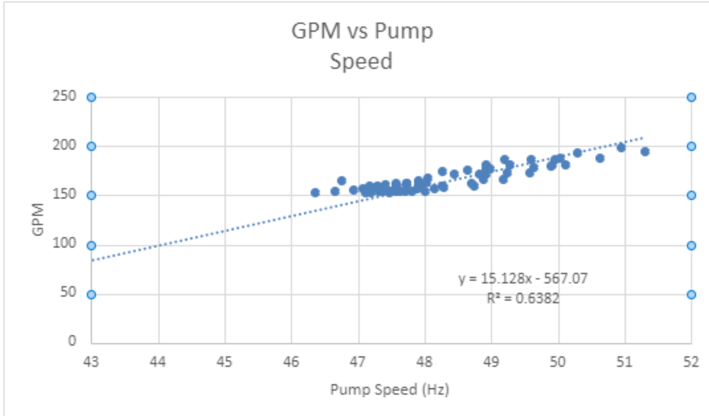
[2] "Fuel Gas." McGraw Hill Encyclopedia of Science & Technology. McGraw Hill, Inc., 1982. https://hypertextbook.com/facts/2002/JanyTran.shtml

Figure 34. GPM Regression



Site 5 - Residential Single-Family Condensing Boiler

Data Collection

Utility bill regressions were utilized to compare residence natural gas use before and after the installation of the nanofluid. Data collection for this site consisted of monthly gas consumption from the utility bills and weather conditions from the nearest NOAA weather station, as summarized in Table 32.

Table 32. Residential Condensing Boiler Data Points

Data Point	Units	Collection Interval (Min)
Outdoor Air Dry Bulb Temperature	°F	60
Outdoor Air Wet Bulb Temperature	°F	60
Total Gas Consumption	Therm	Monthly

Baseline Period

The baseline regression was developed using data from November 17, 2018, to November 15, 2019.

Nanofluid Period

Before data collection for this period, the system was drained and then purged with compressed air. The system was refilled with 18.5 gallons of 47% HYDROMX and 53% water on November 20, 2019. The draining of the system took approximately one hour. The nanofluid regression was developed using data from November 20, 2019, to April 15, 2022.

Site 6 - Residential Four-Plex Non-Condensing Boiler

Data Collection

Utility bill regressions were utilized to compare residence natural gas use before and after the installation of the nanofluid. Data collection for this site consisted of monthly gas consumption from the utility bills and weather conditions from the nearest NOAA weather station, as summarized in Table 33.

Table 33. Residential Non-Condensing Boiler Data Points

Data Point	Units	Collection Interval (Min)
Outdoor Air Dry Bulb Temperature	°F	60
Outdoor Air Wet Bulb Temperature	°F	60
Total Gas Consumption	Therm	Monthly

Baseline Period

The baseline regression was developed using data from November 8, 2018, to November 8, 2019.

Nanofluid Period

Before data collection for this period, the system was drained and then purged with compressed air. The draining of the system took approximately four hours. The system was refilled with 24 gallons of 48% HYDROMX and 52% water on November 15, 2019. The nanofluid regression was developed using data from November 15, 2019, to April 8, 2022.

Appendix C: Detailed Results

Site 1 – Dakota County Water-Cooled Chiller

Outdoor air temperature bins summarize the operation of the Dakota County water-cooled chiller to present the data in an easy-to-consume format.

Baseline Results

Table 34 displays the calculated kW/ton of the chiller system in the baseline condition and other select attributes summarized by the outdoor air (dry bulb) temperature bin.

Table 34. Baseline Results (City Water)

Temp Range	Observations	Avg OAT (°F)	Avg OA WB (°F)	Avg Chiller Ton	Avg Chiller kW	Avg kW/ton	Avg CHW Supply Temp (°F)	Avg Cond Water Supply (°F)
89-87	1	87.0	78.3	96.3	96.1	1.00	41.2	74.7
87-85	68	85.8	77.0	93.6	96.9	1.04	41.4	76.8
85-83	60	84.1	75.7	75.9	89.6	1.18	41.6	76.6
83-81	180	81.8	75.3	58.3	82.0	1.41	42.2	78.4
81-79	292	80.0	74.4	60.4	82.8	1.37	43.6	78.9
79-77	309	78.0	72.6	54.0	73.6	1.36	45.7	76.9
77-75	393	76.1	70.8	47.4	65.9	1.39	50.0	75.4
75-73	416	73.9	68.5	44.4	55.0	1.24	62.2	75.2
73-71	396	72.0	67.4	45.8	66.1	1.44	52.4	75.1
71-69	450	70.0	65.7	54.5	71.2	1.31	52.4	75.1
69-67	507	67.9	64.1	58.8	67.5	1.15	59.8	75.4
67-65	331	66.2	62.4	45.2	57.5	1.27	62.5	74.9
65-63	273	63.8	60.3	41.3	50.3	1.22	68.8	74.8
63-61	190	62.3	58.9	41.3	51.3	1.24	68.6	74.3
61-59	153	59.9	57.4	61.6	70.3	1.14	58.9	75.3

Nanofluid Results

Table 35 displays the calculated kW/ton of the chiller system in the nanofluid condition and other attributes summarized by the outdoor air (dry bulb) temperature bin.

Table 35. Nanofluid Results

Temp Range	Observations	Avg OAT (°F)	Avg OA WB (°F)	Avg Chiller Ton	Avg Chiller kW	Avg kW/ton	Avg CHW Supply Temp (°F)	Avg Cond Water Supply (°F)
93-91	25	92.1	69.3	57.3	90.0	1.571	39.9	75.2
91-89	35	89.8	68.3	57.5	87.5	1.521	41.3	75.1
89-87	30	88.0	67.6	64.1	90.6	1.413	40.7	75.1
87-85	79	85.6	67.3	61.1	88.6	1.450	41.1	74.9
85-83	100	84.2	66.9	60.5	85.1	1.407	41.6	74.8
83-81	108	82.0	65.1	62.5	87.3	1.398	43.3	75.0
81-79	224	79.8	64.6	52.5	84.8	1.616	42.0	75.0
79-77	215	78.2	63.9	55.5	84.2	1.517	42.5	75.0
77-75	320	75.9	62.6	57.7	86.7	1.500	42.5	75.1
75-73	327	74.1	63.0	57.6	83.9	1.456	42.9	74.9
73-71	277	71.9	63.3	60.8	86.4	1.421	44.1	75.4
71-69	441	69.9	61.7	50.3	83.1	1.650	45.2	75.5
69-67	257	68.3	59.9	47.5	81.2	1.709	45.5	75.3
67-65	154	66.1	59.1	45.8	79.5	1.737	46.4	75.1
65-63	204	63.6	61.0	52.4	81.7	1.558	47.9	75.8
63-61	184	62.4	60.6	50.9	78.5	1.541	48.3	76.2
61-59	6	60.6	58.3	65.4	85.7	1.311	51.6	79.3

Comparison

Table 36 compares the differences between the baseline operating period and the operation with the nanofluid.

Table 36. Pre- and Post-Data Comparison (Percent Difference)

Temp Range	OAT (°F)	OA WB (°F)	Chiller Ton (°F)	Chiller kW	kW/ton	CHW Supply (°F)	Cond Water Supply (°F)
89-87	-1.1%	13.7%	33.5%	5.8%	-41.6%	3.0%	-0.5%
87-85	0.3%	12.6%	34.7%	8.6%	-40.1%	2.2%	2.4%
85-83	-0.1%	11.7%	20.3%	5.0%	-19.3%	1.0%	2.4%
83-81	-0.3%	13.5%	-7.1%	-6.5%	0.6%	-3.0%	4.3%
81-79	0.3%	13.1%	13.1%	-2.5%	-18.0%	0.2%	5.0%
79-77	-0.3%	11.9%	-2.9%	-14.4%	-11.2%	-0.9%	2.5%
77-75	0.2%	11.5%	-21.7%	-31.6%	-8.1%	-1.0%	0.4%
75-73	-0.3%	8.0%	-29.7%	-52.7%	-17.7%	-1.2%	0.3%
73-71	0.2%	6.1%	-32.6%	-30.7%	1.5%	-3.2%	-0.3%
71-69	0.2%	6.0%	7.7%	-16.7%	-26.4%	-3.6%	-0.5%
69-67	-0.5%	6.5%	19.2%	-20.3%	-49.0%	-2.6%	0.0%
67-65	0.1%	5.4%	-1.3%	-38.2%	-36.4%	-2.5%	-0.2%
65-63	0.3%	-1.1%	-27.0%	-62.5%	-27.9%	-3.4%	-1.3%
63-61	-0.2%	-2.9%	-23.5%	-53.0%	-23.9%	-2.4%	-2.6%
61-59	-1.2%	-1.6%	-6.2%	-22.0%	-14.8%	-5.6%	-5.3%

Positive values indicate that the parameter was higher during the post or nanofluid operating period. Accordingly, the nanofluid monitoring period occurred when outdoor air humidity was higher. The outdoor air wet bulb temperature averages were more than 10% greater during warmer periods. The increased moisture did not linearly correlate with chiller loading as the difference in chiller loading fluctuated by about +/-35% depending on the temperature bin with no discernable trend.

The chiller power consumption was generally higher during the nanofluid operating period, and the system operated less efficiently (smaller kW/ton values equate to higher efficiency). However, the condenser and chilled water temperatures (CWST and CHWST, respectively) did not appreciably change between the monitoring periods. These water temperatures could affect chiller efficiency if they differed across the two monitoring periods.

Site 2 – Dakota County Air-Cooled Chiller

Outdoor air temperature bins summarize the operation of the Dakota County air-cooled chiller to present the data in an easy-to-consume format.

Baseline Results

Table 37 displays the calculated kW/ton of the chiller system in the baseline condition and other select attributes summarized by the outdoor air (dry bulb) temperature bin.

Table 37. Baseline Results (Glycol-Water)

Temp Range	Observations	Avg OAT (°F)	Avg Tons	Avg Chiller kW	Avg kW/ton	Avg Supply CFM	Avg OA CFM	Avg SAT	Avg MAT	Avg Zone Temp (°F)
87-84	104	85.4	14.3	19.9	1.38	10,947	2,005	62.2	75.8	73.6
84-81	209	81.9	11.0	15.9	1.45	9,393	1,873	63.4	75.0	73.5
81-78	625	79.4	9.2	13.4	1.46	8,650	1,830	64.0	74.6	73.4
78-75	354	76.6	9.2	12.9	1.41	9,102	2,611	63.9	74.4	73.3
75-72	433	73.3	9.1	12.3	1.35	9,146	3,273	63.9	74.3	73.3
72-69	612	70.5	7.9	10.6	1.35	8,862	5,632	64.2	73.5	73.2
69-66	604	67.4	8.2	10.4	1.27	8,867	8,024	63.5	72.6	73.4
66-63	386	64.6	6.2	9.1	1.47	8,208	8,005	64.0	71.4	73.3
63-60	188	61.8	6.2	8.2	1.33	8,528	5,998	64.1	71.4	73.1
60-57	115	58.6	11.1	14.4	1.30	9,413	2,381	62.1	74.7	74.0

Nanofluid Results

Table 38 displays the calculated kW/ton of the chiller system in the nanofluid condition and other attributes summarized by the outdoor air (dry bulb) temperature bin.

Table 38. Nanofluid Results

Temp Range	Observations	Avg OAT (°F)	Avg Tons	Avg Chiller kW	Avg kW/ton	Avg Supply CFM	Avg OA CFM	Avg SAT	Avg MAT	Avg Zone Temp (°F)
99-96	93	96.6	12.2	16.7	1.37	9,357	1,702	61.9	74.7	73.3
96-93	342	94.3	10.8	14.9	1.39	8,884	1,589	62.1	74.6	73.3
93-90	450	91.3	11.7	16.0	1.37	9,444	1,702	61.9	74.6	73.3
90-87	564	88.5	10.9	15.0	1.38	9,135	1,649	62.1	74.5	73.3

Temp Range	Observations	Avg OAT (°F)	Avg Tons	Avg Chiller kW	Avg kW/ton	Avg Supply CFM	Avg OA CFM	Avg SAT	Avg MAT	Avg Zone Temp (°F)
87-84	1022	85.3	11.2	15.2	1.36	9,123	1,632	62.1	74.6	73.2
84-81	1238	82.6	10.3	13.6	1.32	8,380	1,866	62.4	74.5	73.3
81-78	1357	79.4	10.1	13.1	1.30	8,460	2,284	62.3	74.4	73.3
78-75	1680	76.4	10.5	13.5	1.28	8,998	2,170	62.0	74.2	73.2
75-72	1759	73.5	11.1	13.1	1.18	9,352	2,627	62.1	74.0	73.1
72-69	1973	70.5	10.1	12.0	1.19	8,942	3,237	62.5	73.7	73.2
69-66	1182	67.7	10.5	12.1	1.16	9,331	4,807	61.1	72.5	72.8
66-63	952	64.4	10.3	11.6	1.12	8,302	2,944	60.3	72.8	72.5
63-60	666	61.9	11.0	12.6	1.15	9,264	3,051	59.8	72.9	72.2
60-57	228	59.0	7.6	8.2	1.07	6,097	2,300	57.5	72.1	71.8

The metered operating efficiency of the chiller improved by an average of 0.16 kW/ton. The efficiency gains in each temperature bin vary.

Comparison

Table 39 compares the differences between the baseline operating period and the operation with the nanofluid.

Table 39. Pre- and Post-Data Comparison (Percent Differences)

Temp Range	OAT	Air-Side Tons	Chiller kW	kW/ton	Supply CFM	OA CFM	SAT	MAT	Zone Temp
87-84	0%	-22%	-23%	-2%	-17%	-19%	0%	-2%	0%
84-81	1%	-6%	-14%	-9%	-11%	0%	-2%	-1%	0%
81-78	0%	10%	-2%	-11%	-2%	25%	-3%	0%	0%
78-75	0%	14%	4%	-9%	-1%	-17%	-3%	0%	0%
75-72	0%	21%	6%	-12%	2%	-20%	-3%	0%	0%
72-69	0%	28%	13%	-12%	1%	-43%	-3%	0%	0%

69-66	0%	29%	17%	-9%	5%	-40%	-4%	0%	-1%
66-63	0%	67%	27%	-24%	1%	-63%	-6%	2%	-1%
63-60	0%	78%	55%	-13%	9%	-49%	-7%	2%	-1%
60-57	1%	-31%	-43%	-17%	-35%	-3%	-7%	-4%	-3%

Positive values indicate that the parameter was higher during the post or nanofluid operating period. The chiller load and power consumption were generally increased during the nanofluid operating period. However, the system operated more efficiently (smaller kW/ton values equate to higher efficiency).

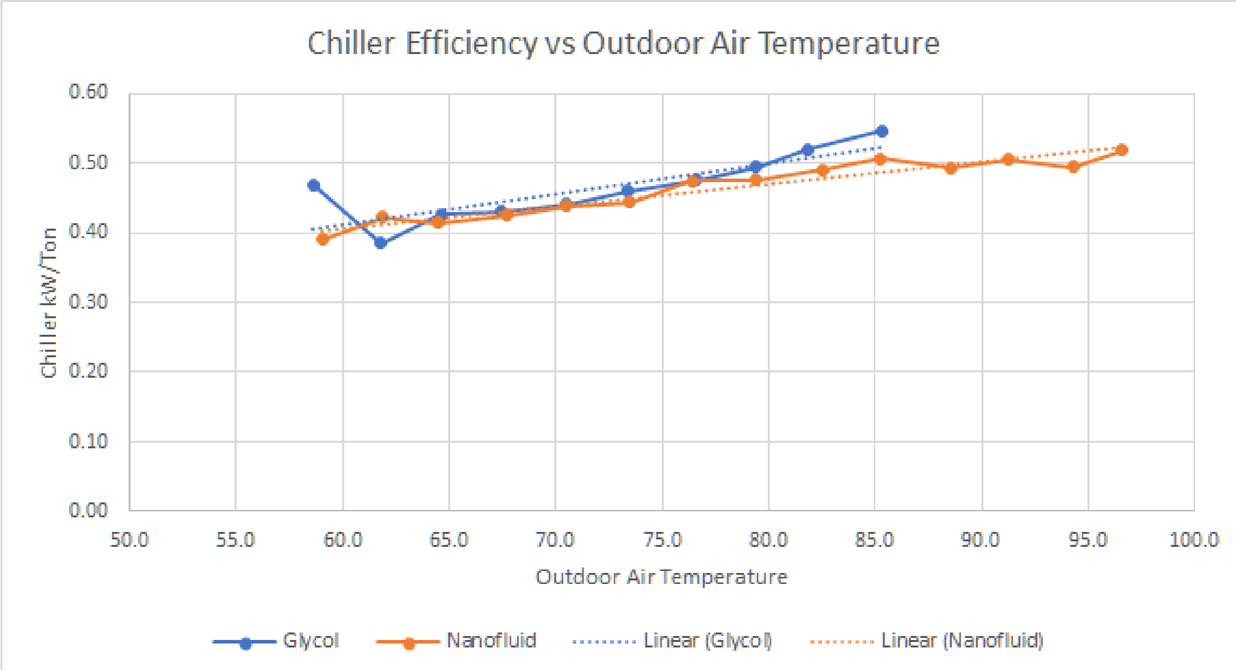
The air handler's total supplied volume (cubic feet per minute, CFM) remained relatively similar across the baseline and nanofluid operating ranges except at the extreme high and low-temperature bins. The amount of outdoor air the air handling unit introduced during the nanofluid operation period appears to be significantly lower than during the baseline operation period. This finding potentially contradicts the assertion from the facility controls technician that the operating sequences did not change during the study. While this finding is interesting, it should not influence the analysis results.

The supply air temperature was slightly lower across all the bins during the nanofluid data collection period. This finding makes sense as the loads were larger during this period, and cooler supply air was required to maintain space temperatures. The air handler's mixed air temperature and the space temperatures of the zones served did not appreciably change between the two monitoring periods.

Alternate Water Side Analysis

Figure 31 and Figure 32 were used to produce the data in Figure 35.

Figure 35. Water Side Efficiency Analysis



This analysis shows 3% annual savings. These findings are problematic because the 0.4-0.5 kW/Ton efficiency values are unreasonably low for an air-cooled chiller rated at 1.23 kW/ton. The project team questioned if the flow rate or chilled water temperature sensors were reporting correctly. The efficiencies shown here are also unreasonably high for the chiller using a standard 30% glycol operating fluid. The project team did not investigate these findings further as they were not part of the original experimental design.

Site 3 – Wooddale Dental Non-Condensing Boiler

Outdoor air temperature bins summarize the operation of the Wooddale Dental non-condensing boiler to present the data in an easy-to-consume format. Only data occurring during the occupied periods are reported.

Baseline Results

Table 40 displays the calculated thermal efficiency of the hot water system in the baseline condition and other select attributes summarized by the outdoor air (dry bulb) temperature bin.

Table 40. Non-Condensing Boiler - Baseline Results (Water)

Temp Range	Occupied Observations	Avg OAT (°F)	Avg VAV Load, BTU	Avg Natural Gas, BTU	Avg Efficiency	Avg HWS (°F)	Avg AHU SAT (°F)	Avg AHU Fan Speed (Hz)
67-63	1	64	11,128	40,600	27%	144.1	69.4	60

Temp Range	Occupied Observations	Avg OAT (°F)	Avg VAV Load, BTU	Avg Natural Gas, BTU	Avg Efficiency	Avg HWS (°F)	Avg AHU SAT (°F)	Avg AHU Fan Speed (Hz)
63-59	18	61	14,731	64,227	17%	145.2	68.4	56
59-55	9	57	5,975	53,795	11%	148.6	68.0	56
55-51	21	53	4,333	50,943	8%	151.6	68.0	55
51-47	24	49	5,245	53,880	8%	154.6	67.9	54
47-43	56	45	8,829	61,516	14%	155.6	67.4	54
43-39	84	41	10,772	66,966	14%	157.9	67.5	54
39-35	112	37	20,802	82,378	23%	160.8	66.4	54
35-31	112	33	29,952	97,685	29%	163.3	65.8	54
31-27	75	29	37,410	108,673	32%	165.3	65.5	54
27-23	73	25	51,734	128,613	39%	168.6	64.4	54
23-19	86	21	51,519	130,191	38%	170.7	63.4	54
19-15	44	17	63,143	144,868	43%	173.7	62.3	54
15-11	23	13	68,004	155,030	43%	176.5	61.2	54
11-7	34	9	88,657	179,088	49%	178.1	60.2	52
7-3	16	5	93,462	194,943	48%	182.1	58.8	51
3 to -1	23	1	102,803	210,061	49%	182.8	57.9	50
-1 to -5	18	-3	109,571	224,597	49%	183.1	56.0	49
-5 to -9	16	-7	114,147	234,782	49%	183.6	54.8	49
-9 to -13	11	-11	119,958	245,999	49%	183.9	54.3	49
-13 to -17	9	-15	124,012	255,329	49%	184.4	52.5	49
-17 to -21	4	-19	126,614	262,631	48%	184.5	51.6	49

Nanofluid Results

Table 41 displays the thermal efficiency of the hot water system in the nanofluid condition and other select attributes summarized by the outdoor air (dry bulb) temperature bin.

Table 41. Non-Condensing Boiler - Nanofluid Results

Temp Range	Occupied Observations	Avg OAT (°F)	Avg VAV Load, BTU	Avg Natural Gas, BTU	Avg Efficiency	Avg HWS (°F)	Avg AHU SAT (°F)	Avg AHU Fan Speed (Hz)
67-63	2	64.0	27,170	79,678	34%	144.6	56.8	60.0
63-59	3	61.4	26,164	80,523	32%	145.5	56.8	55.0
59-55	8	57.3	28,042	90,716	31%	148.7	57.1	58.1
55-51	18	52.8	26,650	84,414	32%	151.4	60.7	58.3
51-47	14	49.0	31,114	90,118	34%	153.6	62.5	57.6
47-43	33	45.3	30,306	92,334	33%	155.5	63.0	57.6
43-39	64	41.5	27,305	93,285	28%	157.9	62.3	54.3
39-35	105	36.8	41,707	113,574	36%	161.2	60.2	56.4
35-31	113	33.0	53,603	127,594	41%	162.4	62.2	57.8
31-27	89	29.6	55,093	132,338	40%	163.7	62.6	54.3
27-23	63	25.4	60,654	140,537	42%	166.6	62.5	54.5
23-19	61	21.5	72,616	160,287	44%	168.4	62.0	54.7
19-15	85	17.0	84,984	175,237	47%	171.5	61.7	55.4
15-11	25	13.3	101,909	195,773	52%	173.8	61.5	56.3
11-7	49	9.1	96,220	201,819	46%	176.5	61.4	57.3
7-3	49	5.5	90,002	195,543	45%	178.8	59.3	55.1
3 to -1	51	0.6	107,578	218,245	49%	182.3	59.3	57.6
-1 to -5	28	-2.9	114,915	231,855	49%	183.2	57.5	54.0
-5 to -9	27	-6.4	118,619	235,330	50%	183.5	58.0	56.0
-9 to -13	12	-9.9	139,784	264,746	53%	183.8	58.4	60.0

Temp Range	Occupied Observations	Avg OAT (°F)	Avg VAV Load, BTU	Avg Natural Gas, BTU	Avg Efficiency	Avg HWS (°F)	Avg AHU SAT (°F)	Avg AHU Fan Speed (Hz)
-13 to -17	5	-14.6	154,428	282,576	55%	183.9	57.6	60.0

The calculated thermal efficiency of the heating loop improved by an average of 9%; however, the improvement in each outdoor air temperature bin varies, with some lower temperature bins showing negative efficiency gains.

Comparison

Table 42 compares the percentage difference between the baseline operating period and the operation with the nanofluid.

Table 42. Pre- and Post-Data Comparison (Percent Differences)

Temp Range	OAT (°F)	VAV Load, BTU	Natural Gas, BTU	Efficiency	HWS (°F)	AHU SAT (°F)	AHU Fan Speed (Hz)
67-63	0%	-144%	-96%	7%	0%	18%	-1%
63-69	-1%	-78%	-25%	15%	0%	17%	1%
59-55	0%	-369%	-69%	20%	0%	16%	-4%
55-51	0%	-515%	-66%	24%	0%	11%	-6%
51-47	0%	-493%	-67%	26%	1%	8%	-6%
47-43	-1%	-243%	-50%	19%	0%	6%	-6%
43-39	-1%	-153%	-39%	14%	0%	8%	0%
39-35	1%	-101%	-38%	13%	0%	9%	-4%
35-31	0%	-79%	-31%	11%	1%	6%	-7%
31-27	-2%	-47%	-22%	7%	1%	4%	0%
27-23	-2%	-17%	-9%	3%	1%	3%	-1%
23-19	-2%	-41%	-23%	6%	1%	2%	-1%
19-15	0%	-35%	-21%	4%	1%	1%	-3%
15-11	-2%	-50%	-26%	8%	1%	-1%	-4%

Temp Range	OAT (°F)	VAV Load, BTU	Natural Gas, BTU	Efficiency	HWS (°F)	AHU SAT (°F)	AHU Fan Speed (Hz)
11-7	-1%	-9%	-13%	-3%	1%	-2%	-11%
7-3	-10%	4%	0%	-3%	2%	-1%	-9%
3 to -1	42%	-5%	-4%	0%	0%	-3%	-14%
-1 to -5	2%	-5%	-3%	1%	0%	-3%	-9%
-5 to -9	9%	-4%	0%	1%	0%	-6%	-14%
-9 to -13	10%	-17%	-8%	4%	0%	-8%	-22%
-13 to -17	2%	-25%	-11%	6%	0%	-10%	-22%

Positive values indicate that the parameter was higher during the nanofluid operating period. The boiler gas consumption was generally higher during the baseline collection period. The measured output, or VAV load, was also higher in the baseline period, especially during milder outdoor temperatures.

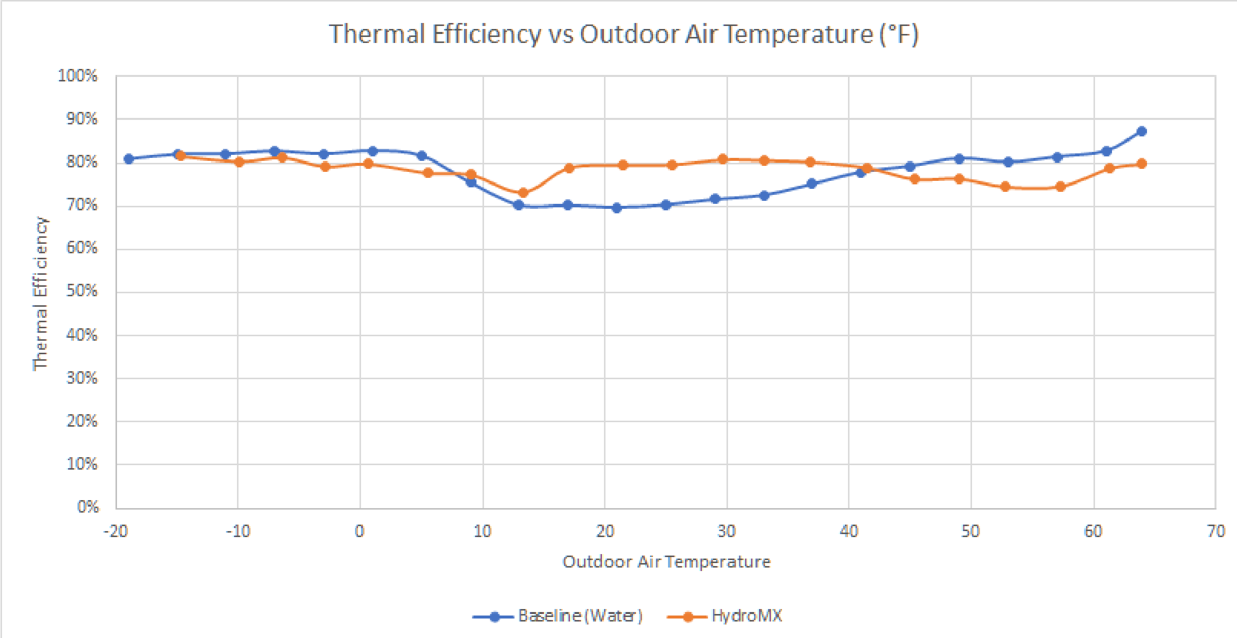
This table shows that the supply air temperature differed between the baseline and nanofluid collection periods. It was warmer in the baseline at some higher outdoor air temperature bins but lower than the nanofluid period at some lower outdoor temperatures. This temperature discrepancy may be related to a control sequence change that the project team was unaware of during the study. The controls contractor could not provide any specifics. Still, the occupancy schedule of the facility equipment did change, so other sequences may have also changed. The occupancy sequence change was accounted for by only comparing data during the occupied periods in the baseline and nanofluid monitoring.

The relationship between the outdoor air temperature and hot water supply temperatures remained consistent across the monitoring periods. Therefore, it can be reasonably concluded that the hot water system operated with a consistent temperature set point reset sequence across the collection period.

Alternate Water Side Analysis

The project team also attempted a water-side efficiency analysis for this site, as all data logging equipment was in place to conduct the analysis. Information from Figure 31 and Figure 32 was used to estimate the physical properties of the HYDROMX solution. Based on those figures, the 50% HYDROMX solution has a specific heat of approximately 0.957 BTU/lb°F at temperatures in the 150-170°F range. A graphical representation of efficiencies is shown in Figure 36 below.

Figure 36. Water-Side Efficiency Analysis



The calculated efficiency of the baseline system using water makes more sense with this water-side analysis, as it shows efficiencies near 80%, which is what the boiler system is rated. However, the HYDROMX analysis shows efficiencies nearly identical to the baseline system. This water-side analysis showed no change in annual energy use for the non-condensing boiler system.

Site 4 – Courage Kenny Condensing Boiler

Hot water supply temperature bins summarize the operation of the Courage Kenny condensing boiler to present the data in an easy-to-consume format. Hot water supply temperature was selected instead of outdoor air temperature because the boiler load does not correlate to ambient weather conditions. Since the facility heating system operates continuously, the summary table includes all hours within the monitoring period, excluding intermittent periods where the BAS did not report values.

Baseline Results

Table 43 displays the calculated thermal efficiency of the hot water system in the baseline condition and other select attributes summarized by the hot water supply temperature bin.

Table 43. Condensing Boiler - Baseline Results (Glycol)

Temp Range	Observations	Avg OAT (°F)	Avg Output BTU	Avg Input BTU	Avg Thermal Eff %	Avg HWS Temp (°F)	Avg HWR Temp (°F)	Avg GPM
158-156	242	3.7	682,072	717,630	95%	156.9	147.1	138.4
156-154	205	10.7	668,384	690,200	97%	155.0	145.3	138.5

Temp Range	Observations	Avg OAT (°F)	Avg Output BTU	Avg Input BTU	Avg Thermal Eff %	Avg HWS Temp (°F)	Avg HWR Temp (°F)	Avg GPM
154-152	350	20.7	504,468	518,230	97%	153.0	145.5	134.2
152-150	333	28.3	527,979	559,622	94%	151.0	143.1	135.0
150-148	524	34.9	524,589	549,808	95%	149.1	141.4	135.1
148-146	500	42.5	475,697	489,839	97%	147.0	139.9	134.4
146-144	351	48.8	450,301	473,667	95%	145.2	138.4	132.7
144-142	213	56.5	418,327	439,357	95%	143.0	136.6	130.4
142-140	95	61.6	454,038	470,105	97%	141.2	134.2	130.5
140-138	48	71.5	424,161	446,177	95%	139.1	132.4	126.3
138-136	12	65.7	506,267	549,792	92%	137.4	129.7	132.2

Nanofluid Results

Table 44 displays the thermal efficiency of the hot water system in the nanofluid condition and other attributes summarized by the hot water supply temperature bin.

Table 44. Condensing Boiler - Nanofluid Results (HMX)

Temp Range	Observations	Avg OAT (°F)	Avg HWS Temp (°F)	Avg HWR Temp (°F)	Avg GPM	Avg Input BTU	Avg Output BTU	Avg Thermal Eff %
170-168	504	36.5	168.4	160.0	103.0	532,472	429,622	81%
168-166	330	30.9	167.2	158.1	107.1	602,848	489,597	81%
166-164	108	20.3	165.0	154.1	117.8	740,574	639,398	86%
164-162	98	14.4	163.1	151.0	123.4	819,250	743,348	91%
162-160	73	10.7	161.0	148.9	130.9	877,349	792,662	90%
160-158	63	10.4	159.1	146.2	131.8	919,944	852,752	93%
158-156	182	4.9	156.9	145.9	134.8	838,769	743,396	89%
156-154	190	6.2	154.8	143.0	139.2	918,842	824,619	90%

Temp Range	Observations	Avg OAT (°F)	Avg HWS Temp (°F)	Avg HWR Temp (°F)	Avg GPM	Avg Input BTU	Avg Output BTU	Avg Thermal Eff %
154-152	214	13.3	153.0	142.0	137.5	853,264	758,667	89%
152-150	190	21.7	151.0	140.8	131.3	775,139	673,977	87%
150-148	322	31.3	148.9	138.8	115.6	694,109	588,116	85%
148-146	219	37.0	147.0	137.6	111.2	628,002	525,248	84%
146-144	167	39.0	145.1	137.5	99.4	567,671	379,739	67%
144-142	100	45.2	143.0	136.3	107.9	509,530	361,231	71%
142-140	64	44.8	141.0	132.5	119.3	658,164	506,945	77%
140-138	34	49.3	139.3	128.9	112.2	662,735	578,779	87%
138-136	9	49.5	136.9	125.1	138.4	958,611	815,461	85%

Comparison

Table 45 compares the percentage difference between the baseline operating period and the operation with the nanofluid.

Table 45. Glycol and Nanofluid Comparison (Percent Differences)

Temp Range	Average OAT	Output BTU	Input BTU	Thermal Eff	HWS (°F)	HWR (°F)	Flowrate GPM
158-156	31%	9%	17%	-6%	0%	-1%	-3%
156-154	-42%	23%	33%	-7%	0%	-2%	0%
154-152	-36%	50%	65%	-8%	0%	-2%	2%
152-150	-23%	28%	39%	-7%	0%	-2%	-3%
150-148	-10%	12%	26%	-11%	0%	-2%	-14%
148-146	-13%	10%	28%	-13%	0%	-2%	-17%
146-144	-20%	-16%	20%	-28%	0%	-1%	-25%
144-142	-20%	-14%	16%	-24%	0%	0%	-17%
142-140	-27%	12%	40%	-20%	0%	-1%	-9%

Temp Range	Average OAT	Output BTU	Input BTU	Thermal Eff	HWS (°F)	HWR (°F)	Flowrate GPM
140-138	-31%	36%	49%	-8%	0%	-3%	-11%
138-136	-25%	61%	74%	-7%	0%	-4%	5%

Positive values indicate that the parameter was higher during the nanofluid operating period. The boiler gas consumption was generally higher during the nanofluid operating period. The load, or measured output, increased at some of the lower water temperature bins; however, the system operated more efficiently in the baseline period. As a result, no consistent pattern could be identified between the glycol and nanofluid results.

The hot water flow rate differed from the baseline (2021) to the nanofluid (2022) data collection periods (as shown in Table 45). The baseline period collected data directly from an ultrasonic flowmeter installed near the pump. However, this flowmeter failed before a complete nanofluid data set could be collected in 2022. The project team could not self-serve data from this site and was unaware of this failure until well after it occurred when the participant provided us with an updated data set. Therefore, the flow rate was estimated using the relationship between the distribution pump motor speed and flow rate. See Appendix B: Analysis Methodology for additional information about that approach.

Site 5 – Residential Single-Family Boiler

Developing Energy Use Models

A linear least-squares regression model of the home's monthly gas usage compared to the heating degree days (HDD) for each month was developed to compare the natural gas usage of the facility before and after the installation of the nanofluid. A simple linear regression formula was used in the following form:

$$Monthly\ Therms_i = slope * HDD_i + intercept$$

Where:

Slope = model-specific constant to represent the Therms of natural gas used per HDD

Intercept = model-specific constant to represent the Therms of natural gas used per month when no heating is required

HDDi = heating degree days for a month using a temperature balance point of 65°F. The balance point chosen for this home provided the best fit for the data

System 6 – Residential Four-Plex Non-Condensing Boiler

Developing Energy Use Models

A linear least-squares regression model of the building's monthly gas usage compared to the heating degree days (HDD) for the month was developed to compare the natural gas usage of the facility before and after the installation of the nanofluid. A simple linear regression formula was used in the following form:

$$Monthly\ Therms_i = slope * HDD_i + intercept$$

Where:

Slope = model-specific constant to represent the Therms of natural gas used per HDD

Intercept = model-specific constant to represent the Therms of natural gas used per month when no heating is required

HDD_i = heating degree days for a month using a temperature balance point of 69°F. The selected balance point provided the best fit for the data