EndoTherm®

Feasibility Analysis for Efficient Heating: Aston University

A Dissertation Submitted to the Department of Sustainable Engineering

Chigozirim Obioma Nnorom - October 2022

FEASIBILITY ANALYSIS OF NON-IONIC SURFACTANT FOR EFFICIENT HEATING: ASTON UNIVERSITY

By

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Abstract

This research focuses on enhancing energy efficiency of heating system at Aston University with the installation of a specific non-ionic surfactant. The dominant explanation for this research is reducing energy demand/consumption. Previous research has primarily focused on the use of surfactant as a drag reducing agent, its effect on heat transfer and on district heating and cooling without trying to understand the effects of change of fluid properties such as density, dynamic viscosity, specific heat capacity, thermal conductivity, and coefficient of volume expansion on heating system performance. There is need to understand the influence of changing fluid properties especially since Aston University considers installing an energy saving non-ionic surfactant developed by Endo Enterprises called Endotherm to help reduce energy consumption and associated costs in operating heating systems. Also, to contribute to personal and corporate goals for reducing carbon footprints.

A model simulation was used to show some of the ways installing surfactant (non-ionic) in a heating system could help reduce energy consumption and case study analysis was used to give an indication of the potential savings likely to be achieved. The results obtained from the simulation showed a 10.62% energy saving for a 10-hour runtime/scenario and a 24% energy saving for a 24-hour runtime/scenario. Showing heating systems with the specified non-ionic surfactant heat up more quickly and maintain a higher temperature for longer, requiring fewer heating cycles over a given time, putting less stress on the boiler, and reducing energy usage. Further simulation analysis on the fluid properties suggested that the lower specific heat capacity of the non-ionic surfactant in use was responsible for the results achieved. Results from the case study analysis showed a potential saving range of 11 to 15% for the identified exemplar building at Aston.

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List of Abbreviations

(DRA) Drag Reduction Agents

(DHC) District Heating and Cooling

(PHE) Plate Heat Exchangers

(CO2) Carbon dioxide

(IEA) International Energy Agency

(CMC) Critical Micelle Concentration

(CMCII) Second Critical Concentration

(HTR) Heat Transfer Reduction

(DR) Drag Reduction

(CHP) Combined Heat and Power Plants

(Ca) Calcium

(Mg) Magnesium

(APG) Alkyl polyglycosides

(BMS) Building Management System

(HDD) Heating Degree Days

(COVID-19) Coronavirus Disease

(IPMVP) International Protocol for the Measurement and Verification of Performance

(ESCO) Energy Service Companies

(ECM) Energy Conservation Measures

1 INTRODUCTION

1.1 Background of Study

A renewed focus on creating and improving energy-efficient sustainable solutions has resulted from the fast-rising demand for power and rising energy costs in cooling and heating applications. In order to do this, district heating systems are regarded as one of the best options for applications involving space heating and cooling. These systems are thought of as alternative energy systems with a lot of energy-saving potential. Large amounts of pumping power are needed for the transmission of both hot and cold water. Energy savings in fluid transfer become a significant issue, particularly when transmission volume or distance is large. This is why fluid transport processes that reduce drag have drawn a lot of interest. By introducing a modest amount of surfactants to the turbulent flow field, it is possible to reduce drag more effectively than with traditional techniques that use solvents, this also accelerates the fluid flow. (Cho et al., 2007). This phenomenon was referred to as Toms effects as it was initially identified in 1948 by B. A. Toms. He discovered that the diluted polymer solution's critical Reynolds number is higher than that of plain water without the additive. (Toms, 1949).

Early research heavily emphasised high-polymer additives and was applied to pipeline transportation. The petrochemical sector was where drag reduction agents (DRA), specifically polymers, first saw commercial use. Polymers have been added to oil in lengthy transmission pipes to reduce pumping power up until this point. The Trans-Alaska Pipeline System, which spans around 800 miles, is the most well-known use. There, DRAs are utilised to successfully decrease the number of pumping stations (Browne 1998). Additionally, polymers are added to heated water surrounding oil to maintain it at a higher temperature and reduce pressure losses (Lucas et al., 2009).

However, the use of polymeric drag-reducing additives has only been permitted for oil pipelines. In district heating and cooling (DHC) systems the strong shear stress found in recirculating pumps, curved pipes, and the near-wall region results in persistent polymer degradation, which reduces the usefulness of polymers in reducing drag (Hara et al., 2019). On the other hand, in surfactant solutions, surfactant molecules group form micelles, which are crucial in reducing turbulence and have the capacity to repair themselves when exposed to secondary forces in the right circumstances. After breaking up after travelling through high-shear regions in recirculation systems, they can quickly reform. The use of a surfactant solution as a liquid heating medium in DHC systems is thus appropriate (Hara et al., 2019). In Herning, Denmark, surfactant solution applications for district heating were carried out on a large scale. Two plate heat exchangers (PHE) were used to isolate the pipes from the rest of the system Similar studies were conducted in Germany and the Czech Republic and significant pressure loss reduction was achieved (Li et al., 2012). In a large-scale test for district cooling, surfactant was added to water in the office building's air conditioning system which had a significant energy saving potential (Takeuchi, 2012).

1.2 Problem Statement and Motivation

Most energy systems depend on heating and cooling processes and the increasing demand for energy-efficient heating systems necessitates the use of novel formulations for improving heat transmission and decreasing energy consumption. Compared to power and transportation, heating and cooling, or thermal energy, is the world's largest source of carbon emissions and should be high on the decarbonization agenda. Decarbonization of heating systems is a crucial goal that supports Net Zero carbon goals worldwide. According to estimates, the sector is responsible for 40% of the world's carbon dioxide (CO_2) emissions related to energy use and approximately half of the world's end-use energy (Royal Society, 2021). Industrial equipment's usable life is further extended by the improvements in heat transfer and energy efficiency brought about by better heating or cooling. Saving energy is made possible by efficient energy use. According to International Energy Agency (IEA) predictions, space heating emissions might be reduced by 30% by 2030 through the use of efficiency enhancements, the substitution of fossil fuels, and decarbonizing electricity generation (IEA, 2021). Energy conservation is unquestionably one of the most crucial issues of this century because, under a "business as usual" scenario, heating and cooling in residential and commercial buildings are anticipated to increase by almost 80% between 2010 and 2050. (Lucon et al., 2014).

Hence it is necessary to improve these thermal management systems, to improve the thermal behaviour of fluids in heat exchangers and district heating systems, new industrial solutions must be devised. Since DHC accounts for a significant portion of global energy consumption, research on DHC's energy-saving practises is essential. Surfactant use in the district heating system can boost flow rate, decrease turbulent flow friction drag, and save energy (Lakhawat et al., 2017). This study examines the practicality of the use of non-ionic surfactant developed by Endo Enterprise to help enhance energy saving and reduce CO_2 emission at Aston University.

1.3 Research Aim

According to background of study, problem statement and motivation, the main purpose of this research is to critically evaluate the practicality and possible effects of the use of surfactant (non-ionic) to help enhance energy saving, its effect on operating cost and carbon emission at Aston University.

1.4 Research Question

1. How surfactant (non-ionic) reduces energy consumption/carbon footprint and associated costs?

1.5 Research Hypothesis

By introducing surfactant (non-ionic) in the building heating system at Aston university, its energy consumption/demand will reduce thus increasing the energy efficiency of the system, reducing its CO_2 emission, and running cost.

1.6 Research Objectives

In order to achieve the aim of this study, the following objectives have been identified:

- i. Identify an exemplar building at Aston University, review the heating system operation in that building to build a clear description of how it is controlled and how it works
- ii. Review of available case study data on the use of non-ionic surfactant, focusing on buildings most similar to those at Aston
- iii. Perform simulation work on a simplified but representative heating system to show one or more of the ways surfactants (non-ionic) can influence energy consumption
- iv. Use the best indicative saving determined from the review of case study data to extrapolate energy saving, carbon emission reduction and cost saving potential.

In the evaluation of carbon emissions, only CO_2 emissions will be examined. Health benefits and other environmental effects aside from CO_2 emissions will not be covered in this research. The simulation will not be able to show net effects over a full heating season, or as occupant behaviours, weather and other factors that influence energy consumption.

1.7 Research Significance

The expected significance of this research is:

i. For writer: This research is expected to give understanding about effect of change of fluid properties on heating system performance and factors that affect the use of surfactant (non-ionic) to help enhance energy saving.
ii. For Aston university: The result of this research will be used as consideration in decision making process on the installation of surfactant in the heating systems.
iii. For academic, this research can give contribution for development and adoption of the use of surfactant (non-ionic) for enhancing energy saving and carbon emission reduction for heating systems.
iv. As scientific documentation: It will be useful for the next researcher that has the same/similar objectives with this research.

2 LITERATURE REVIEW

2.1 Overview

This chapter basically contains reviews on previous studies related to surfactant, classification of surfactants, structural characteristics of surfactant, surfactant as a drag reducing agent, drag and heat transfer reduction fundamentals, the effects of surfactant on heat transfer, the effect of surfactant on district heating and cooling.

2.2 Surfactant

Currently In 1950, Antara product was the first to use the term "surfactant," which is the abbreviation for "surface-active agent." These chemical compounds include at least two components, one of which is lyophilic and is soluble in a particular solvent while the other is lyophobic. This surfactant's dual nature renders it amphipathic in nature (Moroi, 1992). Typically, the terms hydrophilic and hydrophobic are used when discussing water as a solvent. The hydrophobic chain typically has 8–18 carbon atoms and is either linear or branched. Depending on the charge of the molecule, the polar head group can either be ionic or non-ionic. The water-soluble head group is present in the aqueous phase, while the hydrophobic group extends out of the bulk water phase in solution (Holmberg et al., 2003). When a surfactant molecule moves to the surface, it forces the water molecules apart, causing them to lose their hydrogen bonds with one another and lowering surface tension as a result. Surfactants often reduce water's surface tension from 72 to 35 dyne/cm, assisting in the production of emulsions that make spreading between various liquids simpler. Surfactant adheres to the interfaces when it is present in low concentrations (Tiwari et al., 2018).

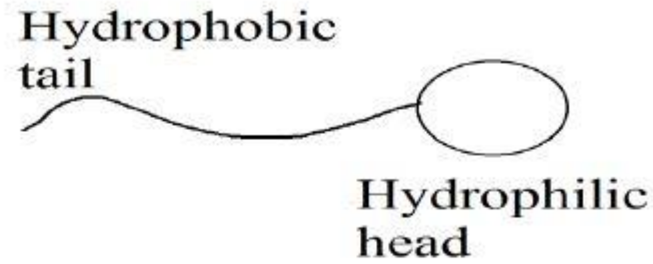

Figure 1. Schematic of a surfactant molecule

Another characteristic of surfactants is their propensity to form micelles, which are aggregates made of monomers. This process of aggregation is known as micellization (Chandra et al., 2014). Critical micelle concentration (CMC) is the concentration at which micelle production first appears. When surfactant concentrations are extremely low, micelles develop, lowering the system's free energy. Micelles are also employed in the solubilization process to improve the solubility of substances that are typically intractable or only marginally soluble in dispersion media. It is the spontaneous conversion of an insoluble material by a surfactant into an isotropic soluble solution (Singh, 2012). The krafft point or krafft temperature is the lowest temperature at which micelle production from a surfactant occurs (Manojlovi, 2012). At temperatures below this, CMC creation does not take place. Therefore, it is a point of phase transition, and above it, the process of micellization causes the surfactant's solubility to increase dramatically. Due to the micelle's ability to weaken the attraction interactions between hydrocarbon chains, the krafft point is achieved. A hazy solution forms when a heated surfactant solution with an oxyethylene group becomes turbid at a specific temperature range. Cloud point is the term for this temperature range. It depends on how long the surfactant's polyoxyethylene chains are. Other aggregates known as lyotropic liquid crystals, which are anisotropic in nature, also develop as surfactant concentration rises (Tiddy, 1980).

Zakin et al., (1998) summarised the micelles production pattern as depicted in Figure 2. In order to generate spherical micelles, the concentration of surfactant must be greater than the critical micelle concentration (CMC). At a concentration over a second critical concentration (CMC_{II}), spherical micelles can transform into rod-like micelles and go on to create network architectures when the flow is sheared. It is clear that temperature and concentration play significant roles in the production of micelles.

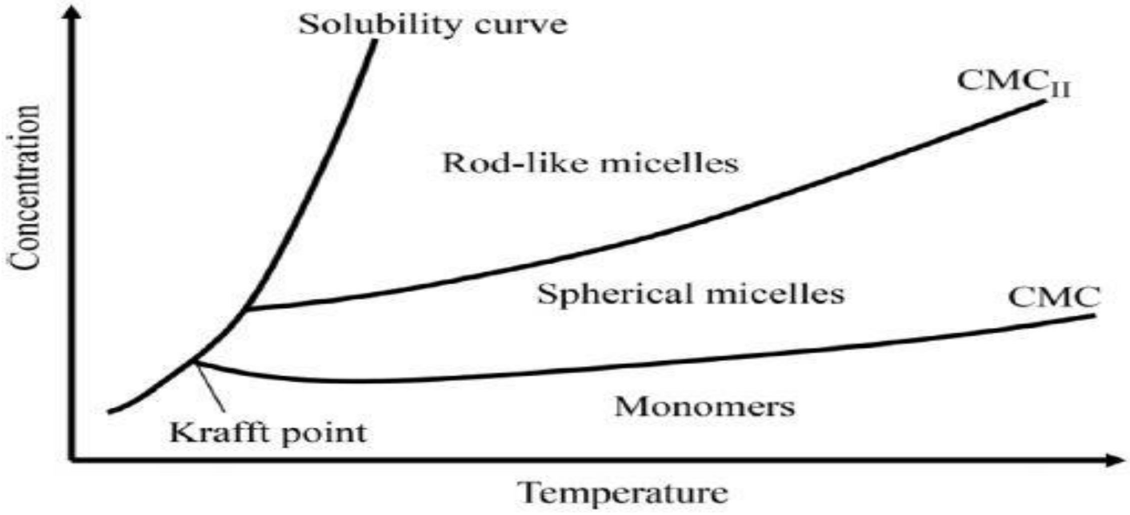

Figure 2. Surfactant solution phase diagram (Gong et al., 2021).

2.3 Classification of Surfactant

Surfactants are classified based on the charge carried by the polar (hydrophilic) portion of the surfactant molecule; a systematic classification of surfactants is provided in Figure 3. Surfactants typically come in the following four types:

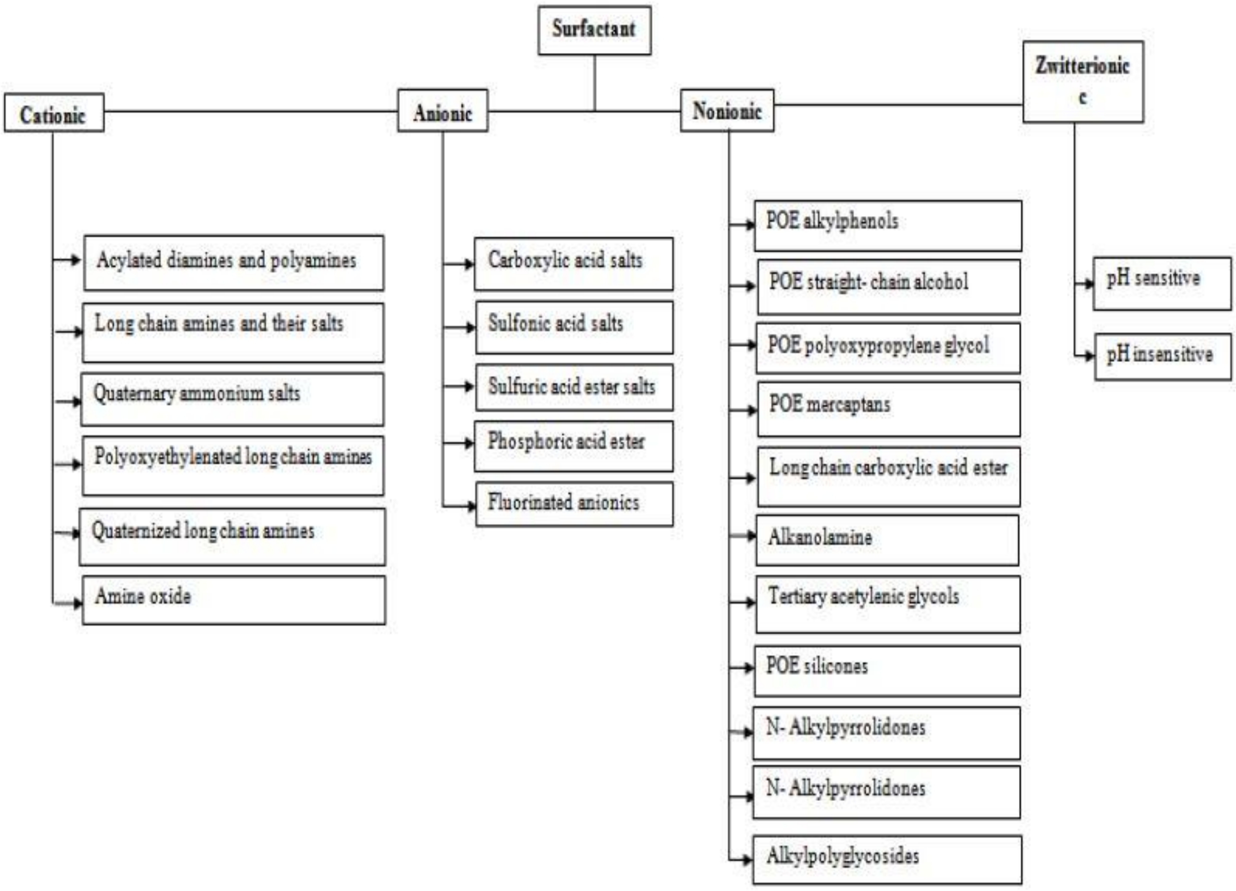

Figure 3. A systematic categorization of surfactants (Tiwari et al., 2018)

2.3.1 Cationic Surfactant

When submerged in aqueous solutions, cationic surfactants have a positive charge as compared to anionic surfactants. Unlike anionic surfactants, these surfactants are not impacted by the metal ions in tap water. Cationic surfactants also offer the advantages of being comparatively stable and having strong self-repairability (Zakin et al., 1998).

2.3.2 Anionic surfactant

When in aqueous solutions, anionic surfactants have a negative charge and are water soluble. However, the calcium and magnesium ions found in tap water might produce precipitation since this surfactant is sensitive to them. The tendency of anionic surfactants to generate foam when exposed to air also contributes to their negative effects (Wang et al., 2011). In many systems that are unable to manage foam formation, this might lead to difficulties. They only have a limited range of application.

2.3.3 Non-ionic surfactant

The head groups of non-ionic surfactants are not charged. These surfactants can self-repair quickly after degrading under high shear and are stable. Non-ionic surfactants have the advantage of being easily biodegradable and less harmful than some other types of surfactants (Zulkifli, 2013).

2.3.4 Zwitterionic surfactant

Amphoteric or zwitterionic surfactants have both positive and negative charges at various locations on their molecules. Zwitterionic surfactants are similar to non-ionic surfactants in that they are likewise rapidly biodegradable and less hazardous than most. Other than that, this surfactant is compatible with all other surfactant classes, soluble in electrolytes, acids, and alkalies, and effective.

2.4 Structural Characteristics of Surfactant

Lyophilic and lyophobic groups make up the unique amphipathic molecular structure of surfactants. Having a hydrophilic group in the aqueous phase and a hydrophobic group distant from it enables the molecule to be oriented at the surface and reduces surface tension.

2.4.1 Surface nature can be changed by the employment of a surfactant

Since surfaces are inherently negative charge, cationic surfactants should be employed to change them into positive charge. Because cationic surfactants absorb on negatively charged surfaces, a lowering of the surface charge results. Similar to how an anionic surfactant, which lowers the charge on the surface and makes it negatively charged, should be employed to convert a cationic surface to an anionic charge. However, because non-ionic surfactants contain both hydrophobic and hydrophilic groups, their orientation depends on the surface's composition and typically does not enough change the charge of the surface. Amphoteric surfactants are capable of adhering to both positively and negatively charged surfaces without altering the surface's charge since they have both positive and negative charges.

2.4.2 The impact of the solvent on the surfactant molecule

Each solvent has a unique impact on the chemical composition of the surfactant molecule. Ionic groups can function as lyophilic groups when utilised as solvents in aqueous solutions like water; however, they can also function as lyophobic groups in nonpolar solutions like heptane.

2.4.3 Effect of change in the hydrophobic group nature on a surfactant

The chemical and physical characteristics of surfactants vary when the hydrophobic group's nature changes, and these changes are as follows:

i. Branching or unsaturation: Adding to or increasing branching or unsaturation in a hydrophobic group can increase thermal instability, decrease biodegradability, bring about oxidation, improve surfactant solubility in aqueous solutions and organic solvents, and lower surfactant melting point.
ii. Hydrophobic group length: Increasing the hydrophobic group length can limit the amount of water-soluble material, compact the surfactant, increase the likelihood of micellization, and improve the sensitivity of the surfactant.
iii. Aromatic group: The presence of an aromatic group can improve surfactant adsorption, lessen its biodegradability, and result in lost surfactant packing (Rosen and Kunjappu, 2012).

Vesicles are formed when surfactant molecules contain phospholipids and two alkyl chains. As membrane models, ionic surfactant-containing vesicles are employed (Hofland et al., 1993). Therefore, the structure of a surfactant gives it significant features that make it one of the most significant and adaptable compounds in modern industrial sectors. Modern research finds a wide range of applications for surfactants in various areas of our daily lives, such as its use as a drag-reducer. This is due to the diversity of surfactant structure and how its capabilities change with changing conditions.

2.5 Surfactant as a Drag Reducing Agent

Surfactants are known as a drag-reducing agent when turbulent flow friction of a fluid in a pipeline system is reduced by adding a small amount of surfactant. Gadd published the first study on surfactant-induced drag reduction (Gadd, 1966). The decrease in turbulence intensity, which underlies the drag reduction with surfactants in aqueous solutions, can be explained by the creation of micelles (Krope and Lipus, 2010). It is clear that temperature and concentration play significant roles in the production of micelles (Gong et al., 2021). There are three theories explaining the observed drag decrease by surfactants. Energy loss is reduced because the processes focus on the area of damping turbulent swirl currents and cross-directional flow. First, when the surfactant is applied to the solvent, it will create entangled rod-shaped micelles. These generated micelles can slow the cross flow because of their elastic qualities (Fontaine et al., 1999). Second, it is seen that the structural micelles have generated an increase in the extensional viscosity. This is what causes the eddy effects to be muted (Shenoy, 1984). Third, these micelles elongate in the direction of the flow, thickening the viscous sublayer of the flow. Eddy currents and cross-directional flow then clash with the thicker sublayer (Kostic, 1994).

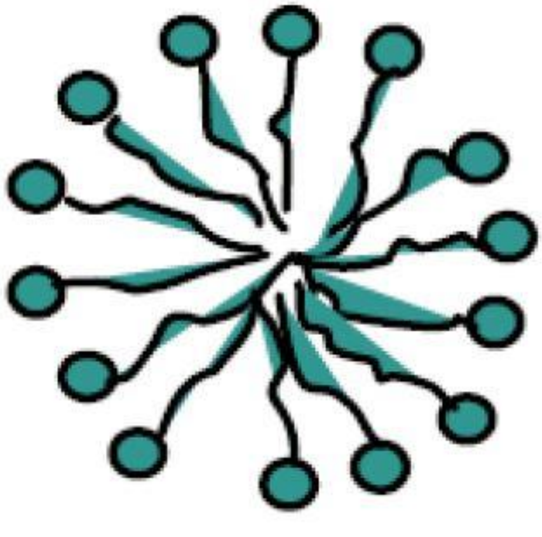

Figure 4a Spherical micelle structure

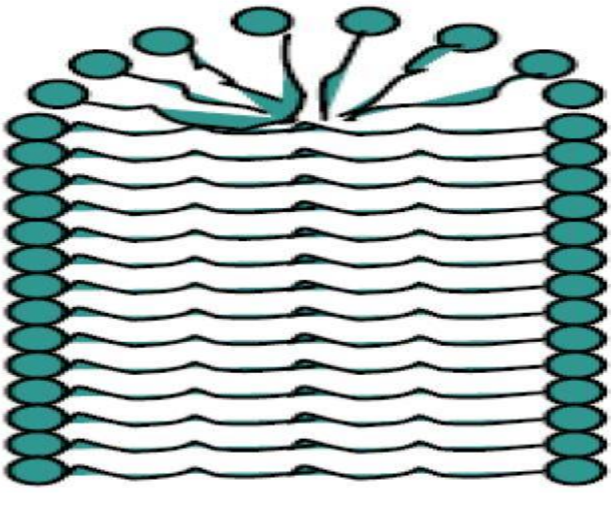

Figure 4b Rod-like micelles structure

2.6 Drag and Heat Transfer Reduction Fundamentals

Drag is the reduction in pressure brought on by wall shear stress and turbulence at high enough Reynolds numbers for the purposes of fluid flow.

The additives that have been discovered to reduce drag essentially reduce the size of the pressure drop caused by turbulence and wall shear stress by as much as 90%. (Zakin et al., 1998). Equation 1 illustrates the mathematical definition of drag reduction (DR) as the percentage reduction in friction between a drag-reducing solution and the solvent alone when compared at the same volumetric flow rate.

$$DR\% = \frac{f_{solvent} - f_{measured}}{f_{solvent}} * 100\% \qquad \text{(Equation 1)}$$

Due to reduced radial turbulence, it has been discovered that drag-reducing solutions also frequently have lower convective heat transfer coefficients (white, 1970). Equation 2 illustrates this phenomenon, known as heat transfer reduction (HTR), as the percentage decrease in the Nusselt number between a drag-reducing solution and the solvent alone when compared at the same volumetric flow rate. It is worth mentioning that the Nusselt number measures the proportion of convective to conductive heat transfer at a fluid boundary.

$$\text{HTR\%} = \frac{Nu_{solvent} - Nu_{measured}}{Nu_{solvent}} * 100\% \qquad \text{(Equation 2)}$$

2.7 The Effects of Surfactant on Heat Transfer

The following are some studies done on how surfactants affect heat transfer, it is complex as surfactant presence in pipe flow typically results in HTR, much like polymer;

Static mixers and honeycombs were positioned at the heat exchanger entrance in the study by Qi et al. (2003) in order to shatter micelle microstructures momentarily and prevent HTR when passing through the heat exchanger. While honeycombs will result in a significantly bigger pressure drop, a decent shape of static mixer may be helpful in boosting heat transfer with only a minor pressure drop cost. Additionally, due to the dissolution of micelles, a considerably greater heat transfer performance can be easily produced in a surfactant solution with a lower concentration.

By installing three distinct rotating agitators inside the inner tube of a concentric tube heat exchanger, Maxson et al. (2017) examined the impact of these agitators on heat transfer in surfactant solution. Agitators' revolving shafts continually scrape the walls and promote mixing, which is good for heat transfer. Micelle structures will be destroyed to prevent HTR when the shear stress reaches the critical value of the surfactant solution with the agitator's increasing rotational speed. The experiments revealed that the use of agitators reduced HTR in surfactant solutions from 60% to 20%, and that agitators can be more energy-efficient than previously researched static mixers, as demonstrated by Qi et al., (2003) and Shi et al., (2011).

When surfactant solutions were utilised as the fluid medium, Gasljevic et al. (2017) investigated the impact of temporary intentional mechanical degradation on the heat exchanger in recirculating systems. The findings showed that wire mesh inserts were suitable and effective as the other mechanically degrading ways, and that purposeful mechanical deterioration was a practicable way to get rid of HTR.

In a laminar flow at mini-scales, Hetsroni et al. (2004) investigated the drag reduction (DR) and heat transmission of surfactant solutions. The researchers used a capillary tube with an inner diameter of 1.07 mm and a Reynolds number range of 10 to 450 to assess the pressure drop and heat transfer coefficient in fully developed laminar flow. Using Habon G solutions results in a greater pressure drop in both adiabatic and diabatic flows as well as a greater heat transfer coefficient at the same velocity when compared to water. When compared to turbulent flow, the outcomes are considerably different. According to the authors' reasoning, secondary flows may result from the surfactant solution's fluid elasticity, which raises pressure drops and the coefficient of heat transfer.

In pipe flow with an impinging jet, Mizunuma et al. (2010) studied the heat transfer of a surfactant solution with excessive counterion. HTR was observed in pipe flow, but it could be prevented in an impinging jet by adding a counterion at a molar concentration 30 times greater than the surfactant. They attributed it to the many micellar structures that were deforming compressively during the impinging flow. The simultaneous realisation of DR and regular heat transmission in a circulating heat exchange system was made possible by deploying this surfactant system in an impinging jet. This study offered a helpful concept for the use of surfactant.

Because of the shift to smaller combined heat and power plants using alternative fuels, solar plants, and heat pumps, where plate heat exchangers can be employed, Kotenko et al., (2019) noted that the drop in heat transfer in shell and tube heat exchanger may disappear or diminish. As a result, it will be simpler to reach a critical shear stress, which will cause the bonds between the surfactants to dissolve and cause the solution to behave like water.

Additionally, Klein et al., (2005) Hetsroni et al., (2001) and Morgan et al. (1949), as well as other researchers, have shown that adding surfactants can improve boiling heat transfer. The improvement in heat transfer was attributed by Morgan et al. (1949) to the use of surfactants, which decreased surface tension. According to Hetsroni et al. (2001) findings, the boiling heat transfer coefficient of a Habon G solution increased by up to 100% when compared to water. Boiling with added surfactants has a bright future. Table 1 summarises previous study findings in terms of two flow regimes: turbulent and laminar heat transfer.

Table 1. Summary of the heat transfer characteristics studies on surfactant solution

Year	Authors	Surfactant	Flow Condition	Conclusion
2003	Qi et al.	Cationic and mixed zwitterionic/anionic	Turbulent	Lower surfactant concentrations may help the surfactant solutions' microstructure to break up and improve heat transmission.
2004	Hetsroni et al.	Cationic	Laminar	Surfactant solutions increase the pressure drop in adiabatic and diabatic flows, as seen by the dependency of the pressure drops on bulk velocity.
2010	Mizunuma et al.	Cationic and counterion	Turbulent	In the impinging jet trials, surfactant solutions with molar ratios between 30 and 100 did not exhibit

				any reduction in heat transfer, and since drag reduction in pipe flows increases flow rate, a higher rate of heat transfer in an impinging jet may be anticipated.
2017	Maxson et al.	Cationic	Turbulent	Using agitated heat exchangers, significant reductions in HTR were made for surfactant DR solutions.
2017	Gasljevic et al.	Cationic and non-ionic	Turbulent	In systems where surfactants are utilised as drag-reducing additives, intentional mechanical degradation appears to be a workable way to reduce or eliminate the heat transfer reduction in heat exchangers.
2019	Kotenko et al.	Zwitterionic and anionic	Turbulent	Due to the transition to smaller combined heat and power plants (CHP) using alternative fuels, solar plants, and heat pumps, where plate heat exchangers can be employed, the problem of reduced heat transmission in shell and tube heat exchanger may no longer exist.

2.7 Effect of Surfactant on District Heating and Cooling

The following are some of the researches carried out on heat transfer effects of surfactants on district heating and cooling;

In Herning, Denmark, transmission twin pipes with a diameter of 200 mm and a length of 2,8 km underwent full-scale uses of surfactant solution for district heating (Hammer, 1999). With the use of two plate heat exchangers, pipes were separated from the rest of the system. The study's findings indicated that a significant reduction in pressure loss of 70 to 80% had been made.

Additionally, Volklingen, Germany, and Prague, Czech Republic, conducted related studies (Li et al., 2012). District cooling is another use where surfactants should be made for temperatures between 5 and 45 degrees Celsius. In a large-scale test, water in the office building's air conditioning system was augmented with surfactant in Japan. The amount of energy saved throughout the cooling time was 47% (Takeuchi, 2012). Additionally, the impact of various molecular structures was investigated. The effectiveness of non-ionic surfactants is constrained by the limited temperature range for effective drag reduction. Application of anionic surfactants is constrained by precipitation brought on by bivalent ions such as calcium (Ca) and magnesium (Mg) in hard water. Due to their wide temperature range and lack of sensitivity to Ca and Mg ions, cationic surfactants have been the subject of much research. It was discovered that the top temperature limit for efficient drag reduction increases as the length of the alkyl chain grows (Yang, 2012).

Due to a heat transfer reduction issue in the shell and tube heat exchanger, studies were discontinued. At the moment, district heating application studies for DRA are concentrated on finding answers to issues like decreased heat transmission in heat exchangers by applying various techniques for straining the flow over its path (Li et al., 2012). These studies also examine several characteristics, such as critical concentrations and critical temperatures, that can aid in determining the ideal operating ranges for drag reducers (Maxson et al., 2017).

In Sweden, a more recent study was conducted on the impact of surfactant on district heating and cooling. Beraids, which are composed of the two surfactants zwitterionic and anionic, were used by Kotenko et al. (2019). Harwigsson and Hellsten (1996) were the first to study these combinations. The working fluids investigated are AkzoNobel's Beraid DR-IW 616 and 618 for aqueous solutions. Both products include the same type of surfactants but are constructed differently to accommodate various temperature needs. Tests on Beraid DR-IW 616 were conducted separately at the AkzoNobel facility in Sweden. An analysis of Beraid DR-IW 618 was conducted at Aalborg University. The results of the experiments show that Beraid DR-IW 616 has a greater maximum drag reduction of 70–80% than Beraid DR–IW 618, which is between 60–75%. These studies were conducted in pipes of various diameters. Differences in pipe sizes can result in changes in pressure loss reduction, which helps to explain why Beraid DR-IW 618 has a lower effect (Gasljevic et al., 2001).

The development of more environmentally friendly surfactants and the modification of suitable mechanical systems for such applications are both necessary for the widespread use of drag-reduction surfactants. The degree to which a surfactant can improve efficiency in a heating system also depends on the amount of concentrations, chemical makeup, wall heat flux, and heating surface geometry as primary goal of introducing surfactant is to reduce drag and thereby save energy. There is also need to understand the effect of changing fluid properties on heating system performance especially since Aston university considers using a commercial product produced by Endo Enterprise that claims to offer savings. From a scientific literature point of view Endo Enterprise is claiming something which is not being discussed in any literature so far therefore making this study important.

3 METHODOLOGY

3.1 Overview

The preceding chapter mostly focused on the review of the relevant literature for this research; this chapter highlights the procedures, justification, and analytical techniques used for this research.

3.2 Research Design

Positivist paradigm study was employed for this research considering the research questions, this requires I take a quantitative method approach and secondary data was utilised as my data source.

The surfactant under investigation in this study is a product called endotherm additive which is a non-ionic surfactant. Yaseen's (2016) analysis revealed the commercial Endotherm mixture contained lesser levels of the two-maltose sugar alkyl polyglycosides (APG) and the single sugar unit, n-Octyl-D-Glucopyranoside. Alkyl polyglucosides hydrophilic moiety, unlike that of non-ionic ethoxy surfactants is derived entirely from the saccharide head group. Due to their compatibility and synergistic benefits when mixed with other surfactants, as well as their comparatively low toxicity and negligible environmental impact, APG has drawn growing interest. It is worth mentioning that the dose rate is 1% of system volume.

To be able to predict what sort of benefits Aston university could get from installing surfactant in its heating system I could:

i. Develop/carry out a building full building simulation; When done appropriately this could give awful lot more information about what the benefits are when the results are out and could be translated to the buildings. Although there no ideal models out there that could do that and the time it will require to complete the whole modelling doesn’t make it appropriate for this study. For this, I will be simulating a simplified but representative heating system. The simulation will help with the comparison of the effect of water alone in a heating system and the effects surfactant (non-ionic) when is introduced in heating system.

ii. Perform an experiment on the building; The experiment of the building will have to happen over the heating season, which means it won’t be completed for another six months and therefore it is not appropriate for this project considering time and financial constraints.

iii. Look into existing case study data; This is relatively quick and will give indications of what the actual benefits of using surfactant in a heating system might be, but it is probably the least relevant it is a different building. Because it is relatively quick and will be able to give indications of possible savings might be, I will do it anyway.

iv. Carry out laboratory experiments; Focus on laboratory experiment considering steady state won't appropriately show the impacts of the use of surfactant as it is used in an unsteady state in a realistic approach. Time constraint makes it inappropriate for this project to fully consider the effect on unsteady state.

Therefore, for this study my approach to answer the research question is two things in parallel, first is a model (simulation) that will allow me to explain some of the physics involved in introducing a surfactant in a heating system and the second is analysis of case study data.

3.3 Simulation Method

A modelling tool called cascade modelling of fluid systems develop by Dr Andrew Williams while still working at Chester University was employed to perform simulation work on a simplified but representative heating system to show the effects surfactant on energy consumption. The core part of this model is the fluid system and heating system of the building. The physics this piece of software is resolving is the newton second law and first law of thermodynamics for unsteady incompressible flows in pipe networks where any single pipe has the same inlet and area. It also models the building using a lumped capacitance model.

Its solution method/process of Newton second law is outlined below:

i. Any pair of connected pipes can be combined to create a composite element that has the same dynamical properties as the original pair.

ii. These connections enable composite pieces to take the place of connected pipes until a single pipe is used to represent the whole network.

iii. In this single pipe, the rate of change of mass flow can then be calculated.

iv. This will be equivalent to the rate of change of mass flow in the sub elements for composite elements that are connected in series, allowing estimation of the stagnation pressure distribution through that composite element.

v. Because the pressure is the same in both pipes for composite elements that are connected in parallel, it is possible to calculate the rate at which the mass flow through each pipe changes.

vi. This cascades down through the system's many levels until all pressures and the rate at which mass flow changes are known, allowing the conditions at the next timestep to be predicted.

The thermal model for the pipe network is an unsteady quasi two-dimensional finite volume model. The room are well mixed thermal masses coupled with thermal resistances. (Uses an explicit unsteady solution).

The simulated system consists of a boiler, two pipes and a radiator that are connected in series for one room. Table 2 shows the input conditions for the system and fluid properties considered. Most of these values are inline available in the literature while some where defined values in the model.

Table 2. Input conditions and fluid properties considered for the simulation

1.	Pipes	The pipes are made of copper with a surface roughness of 0.000001 m, pipe hydraulic diameter of 0.02 m, wall density of 8900 kg.m^{-3}, wall thickness of 0.001 m, wall material specific heat capacity of 385 J.kg-1.k^{-1}, wall material thermal conductivity of 385 W.m^{-1}.k^{-1}, material initial temperature of 290 K.
2.	Radiator	The radiator is made of steel with an effective surface roughness of 0.00001 m, radiator hydraulic diameter of 0.11 m, wall material density of 7900 kg.m^{-3}, wall thickness of 0.002 m, wall material specific heat capacity of 445 J.kg^{-1}.k^{-1}, wall material thermal conductivity 80 W.m^{-1}.k^{-1}, material initial temperature of 290 K.
3.	Boiler	Maximum boiler power rating of 35000 W (the high-power boiler used was due large system flowrate), initial element temperature 290 K, hydraulic diameter of 0.2 m

4.	Room	The room has an initial bulk temperature of 290 K, External heat transfer coefficient is 20 W.m^{-2}.K^{-1}, Heat Capacity of 200000 J.K^{-1}, thermal resistance between room and surrounding is 0.17 K.W^{-1}
5.	Fluid Properties (Water)	Density: 1000 kg.m^{-3}, dynamic viscosity: 0.0004 Pa.s, specific heat capacity: 4186 J.kg^{-1}.K^{-1}, thermal conductivity: 0.6 W.m^{-1}.K^{-1}, initial temperature 290 K, coefficient of volume expansion: 0.00021 K^{-1}
6.	Fluid Properties (Endotherm)	Density: 1002 kg.m^{-3}, dynamic viscosity: 0.00042 Pa.s, specific heat capacity: 3767.4 J.kg^{-1}.K^{-1}, thermal conductivity: 0.588 W.m^{-1}.K^{-1}, initial temperature 290 K, coefficient of volume expansion: 0.00021 K^{-1}

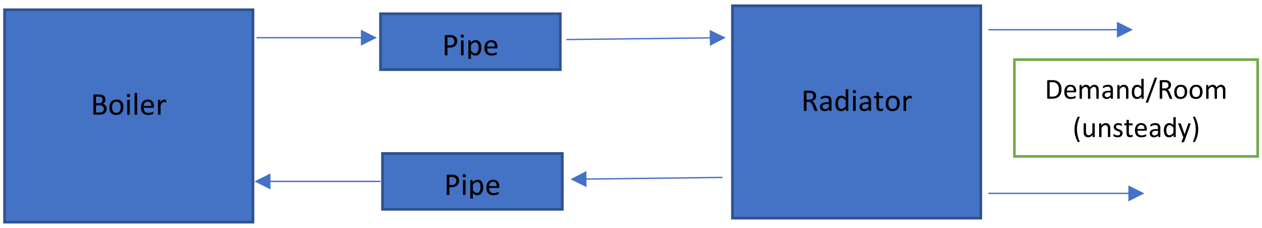

Figure 5. System diagram of the model (simulation)

The two fluids considered in this simulation were diluted Endotherm in water (at 1% system volume concentration) and water alone, the simulation was performed with an ON/OFF timer control and thermostat with a maximum temperature of 21°C (294 K) and minimum temperature at 20°C (293 k). The boiler set point at 40 degrees. Two different time scenarios were performed, the first scenario/scenario one lasted for 10 hours with the heating system commencing by 8am (28800 seconds) and ending by 6pm (64800 seconds) while the second scenario/scenario two was for a 24-hour period (86400 seconds) period. I'm aware that I also need to consider internal generation and the occupant behaviour, but I haven't got the time to do it.

3.4 Case Study Method

The identified exemplar building for this study is the Aston main building, the building is a multi-story building, multi-rooms heated by water through heat emitters, connected to a district heating system which has the following characteristics: It is occupied from Monday to Friday and heated to a lower temperature on weekends. Review of the building management system (BMS) as provided by the Estates and Capital Developments shows that the main building heating is fed from the district heating from the main boiler house. This is controlled by others. Once the district heating is fed into the main building, there are 4 x plate heat exchangers which control the heating flow temperature dependant on the outside air temperature. A detailed review of the Aston main building BMS can be found in (Appendix A).

Various published case studies can be found on product website and some criteria were employed to identify the most relevant cases to the study and remove less relevant case study after the identification and review of the building management system was performed such as:

i. Removal of case study that is not on a multi-story building
ii. Removal of case study with a different building size
iii. Removal of case study with buildings used in a completely different way (only used on weekend rather than 5days every week).

Therefore, I can look through Endotherm case studies for building with these characteristics. After applying the identified criteria listed above, I was left with 25% of the total amount of cases found on the company website. Details of the investigated case studies can be found in (Appendix B).

Table 3. Typical annual energy data at Aston main building (identified exemplar building)

Building	**System**	**Heat Transfer**	**Typical Annual Energy**	**Typical annual heating cost**
Main Building	‘A’ Corner Variable Temperature Heating System	Water to Water PHEX	1,600,000 kWhr / annum	£93k

Main Building	‘C’ Corner Variable Temperature Heating System	Water to Water PHEX	1,600,000 kWhr / annum	£93k
Main Building	‘E’ Corner Variable Temperature Heating System	Water to Water PHEX	1,600,000 kWhr / annum	£93k
Main Building	‘G’ Corner Variable Temperature Heating System	Water to Water PHEX	1,600,000 kWhr / annum	£93k
South Wing	Variable Temperature Heating System	Water to Water Shell-in-tube HEX	1,100,000 kWhr / annum	£64k
North Wing	Variable Temperature Heating System	Water to Water PHEX	1,100,000 kWhr / annum	£64k

The figure shows details on the heating systems, energy consumption data and costs for the Main Building, North Wing and South Wing at Aston University campus as provided by Estates and Capital Developments, this was used to determine the potential energy, cost, and emissions savings at Aston. 0.216 kg/kWh was used as the gas emission factor (Amirkhani et al., 2020).

4 RESULTS AND DISCUSSION

4.1 Overview

This chapter explains about the result and discussion obtained from the analysis of the case study and simulation carried out. It also highlights the implication, limitations, and future work of the research.

4.2 Result from Simulation

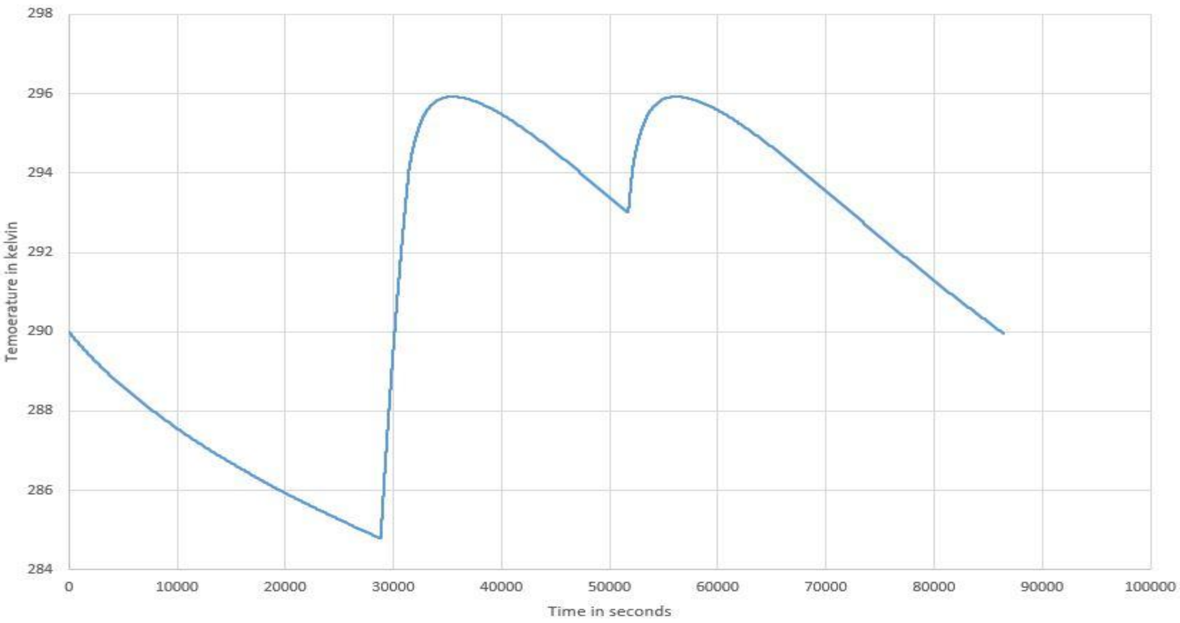

Figure 6. Scenario one: An overview of the room temperature behaviour

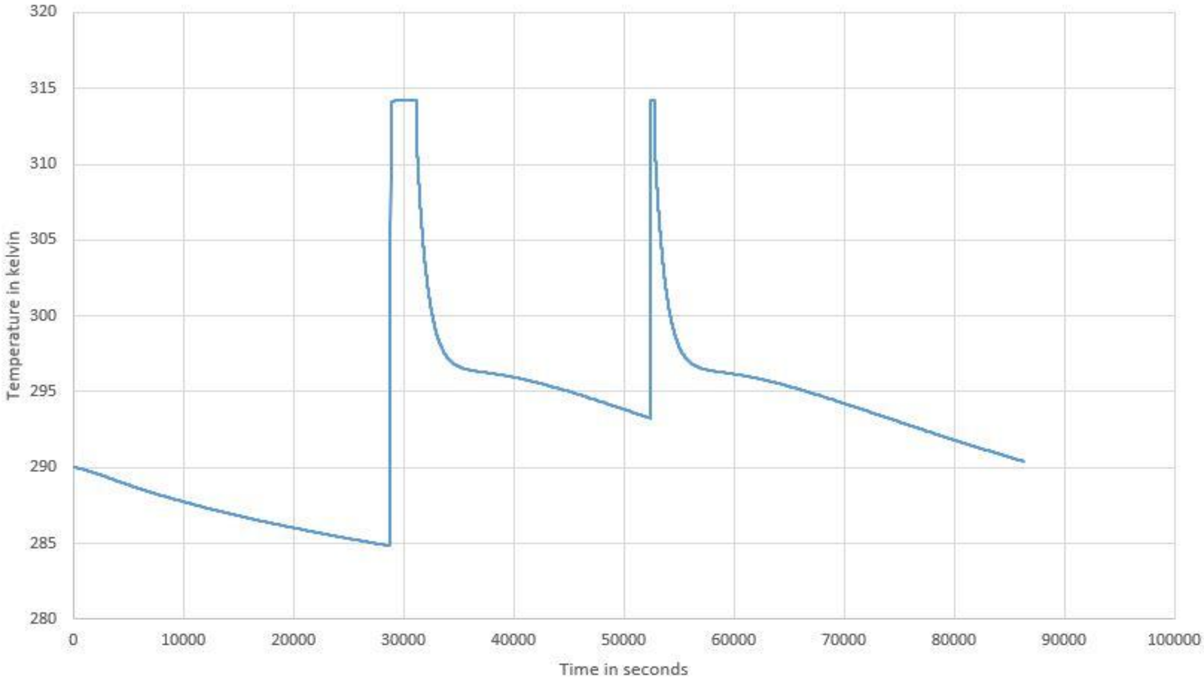

Figure 7. Scenario one: An overview of the water temperature behaviour

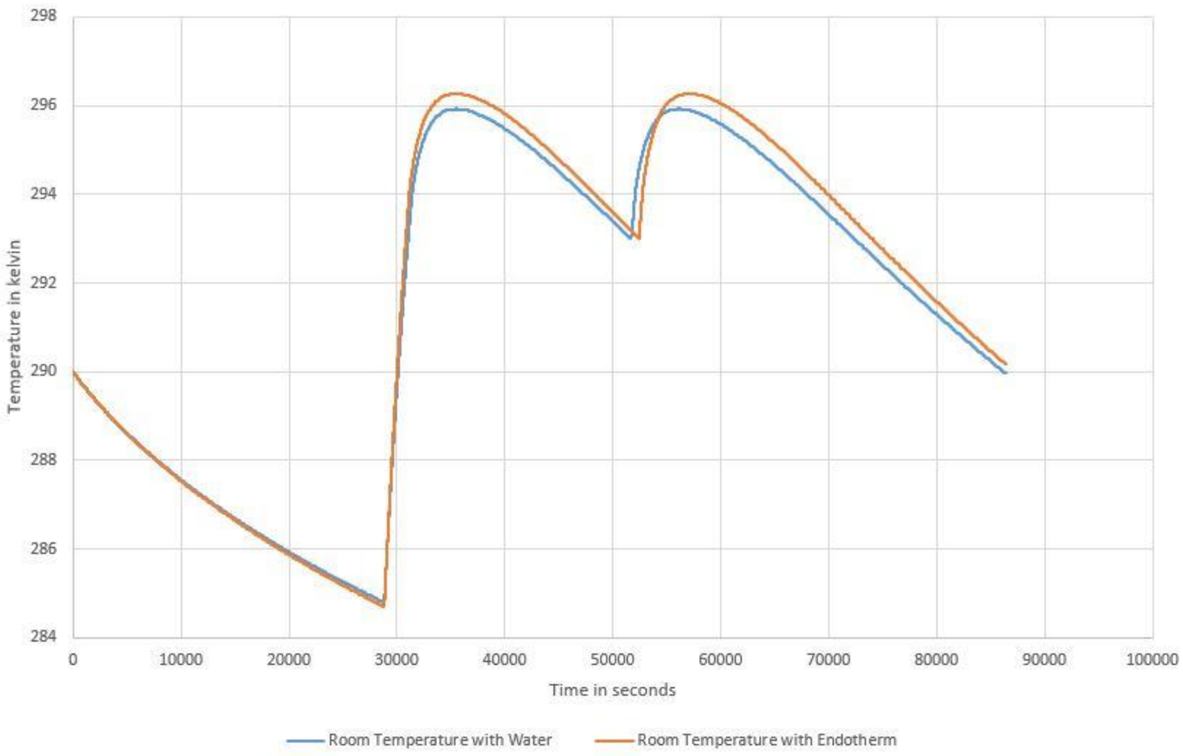

Figure 8. Scenario one: Comparison of the room temperature behaviour with water and addition of endotherm

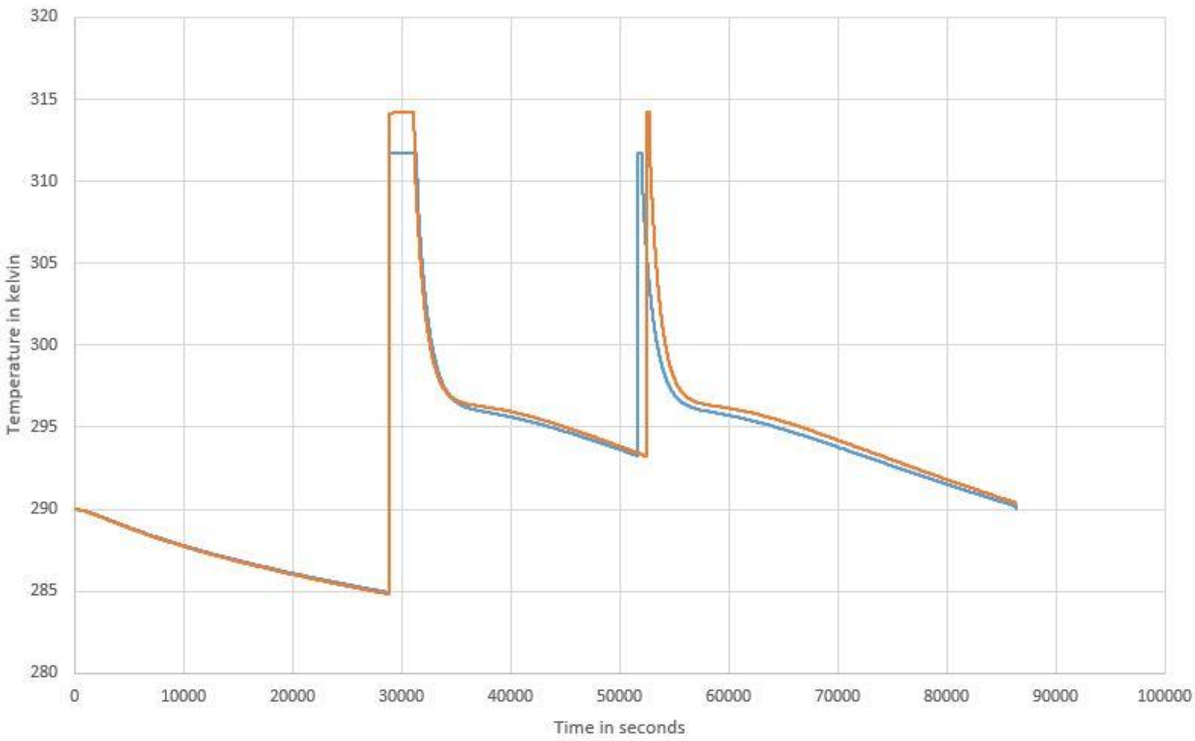

Figure 9. Scenario one: Comparison of the water temperature behaviour with water and addition of endotherm

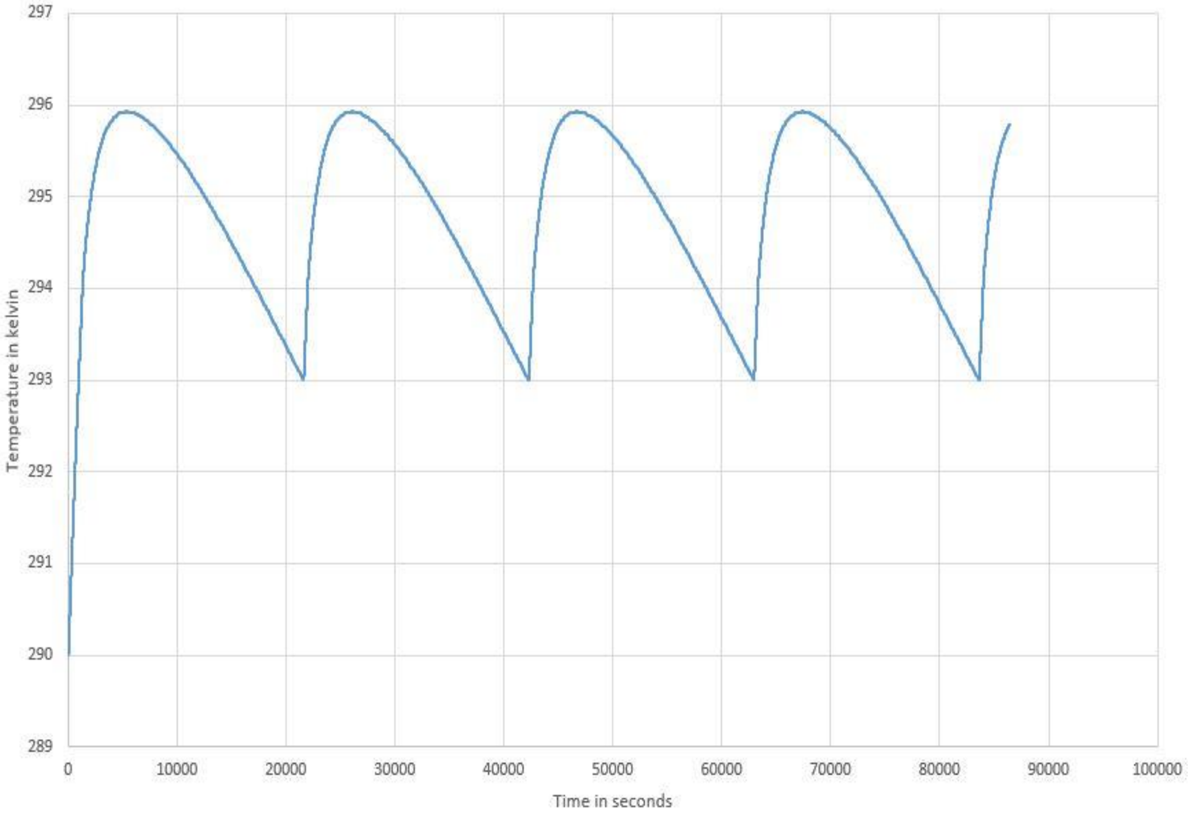

Figure 10. Scenario two: An overview of the room temperature behaviour

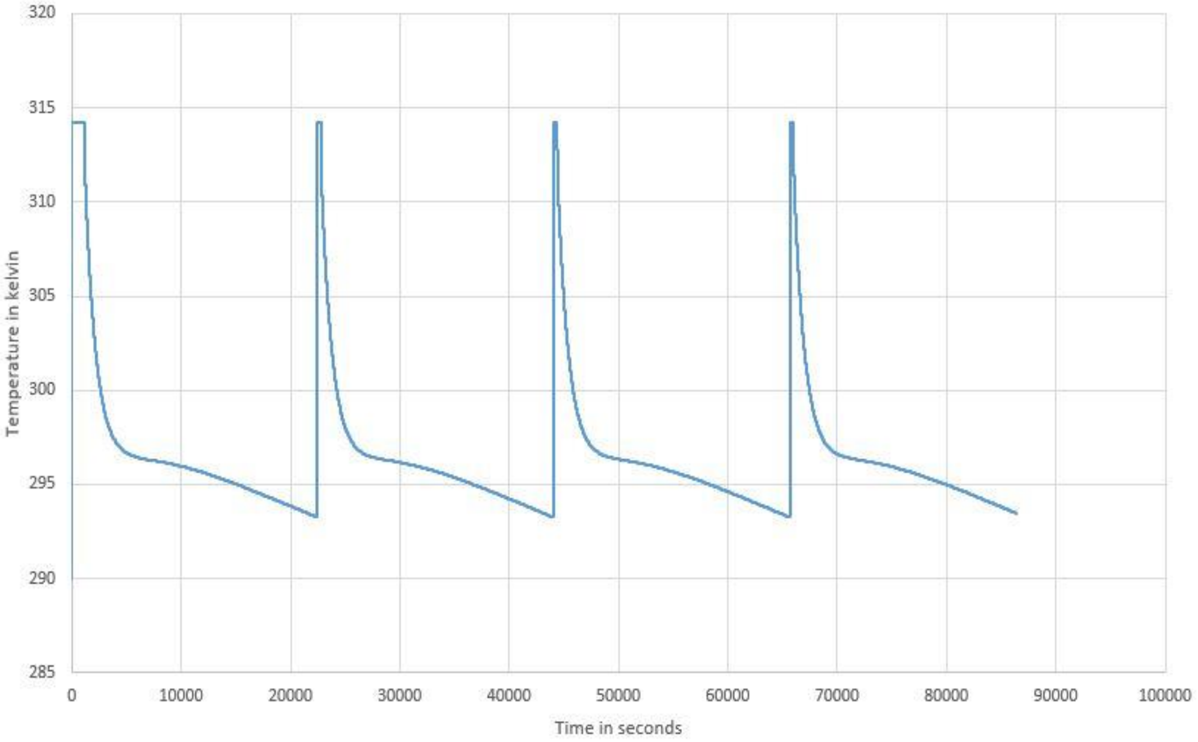

Figure 11. Scenario two: An overview of the water temperature behaviour in the simulated heating system

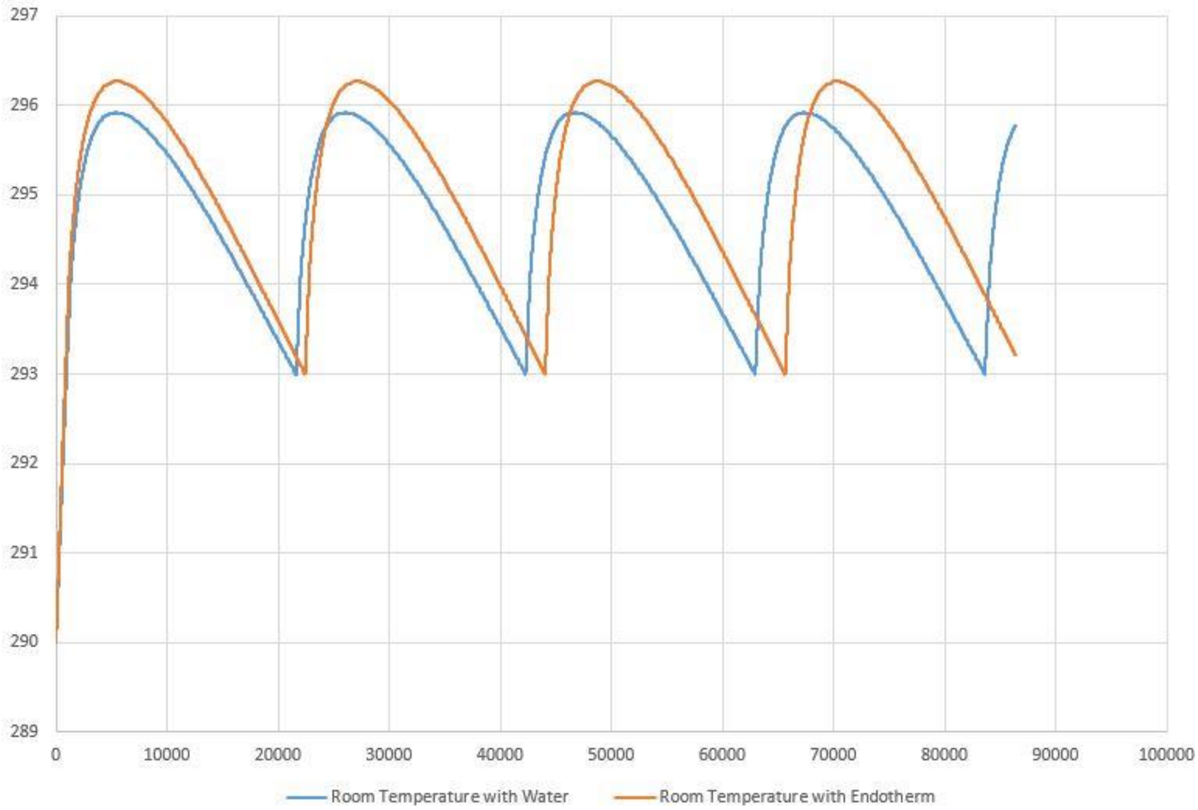

Figure 12. Scenario two: Comparison of the room temperature behaviour with water and addition of endotherm

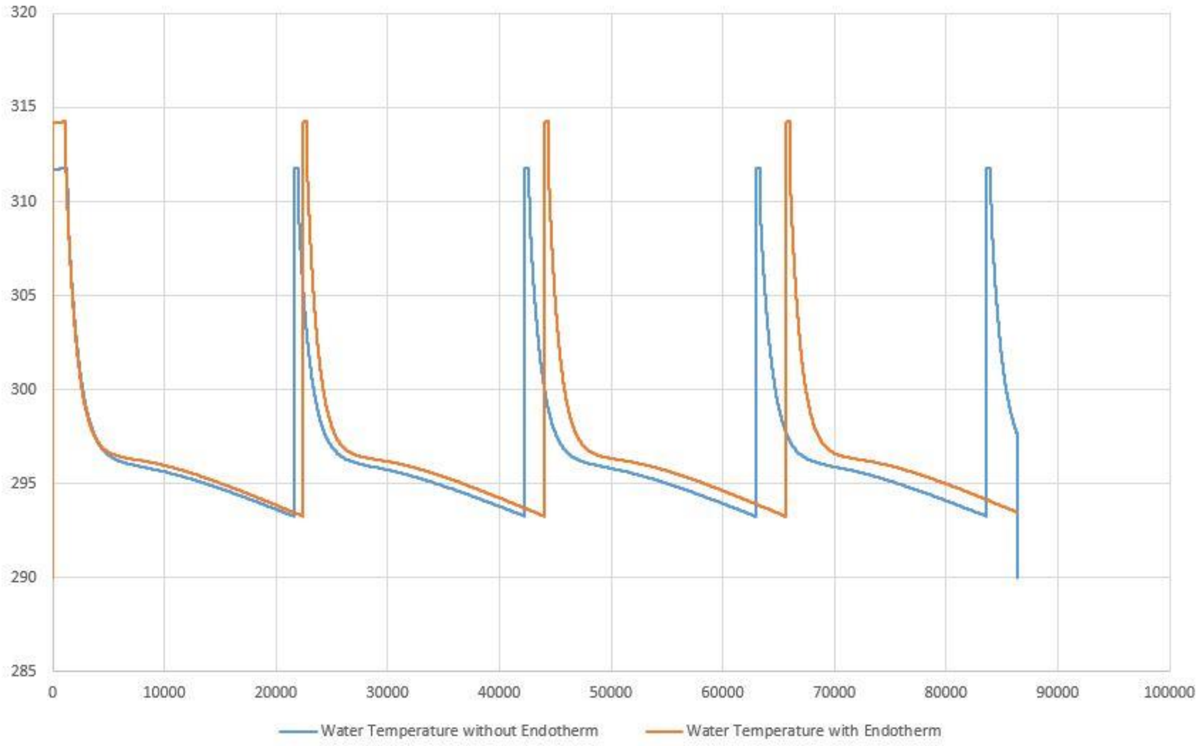

Figure 13. Scenario two: Comparison of the water temperature behaviour with water and addition of endotherm

The overview in figure 1. For the first scenario showed the gradual decline of the room temperature before the heating commenced at 28800 seconds (8 am). From the system control, the thermostat is set to switch OFF the system at temperature above 294.15K and switch it back ON at temperature below 293.15K, this is shown on the figure. The continuous increase in the room temperature up to 296K is as a result of the radiator still filled with hot water and takes a while before it starts cooling down. Figure 2. showed the gradual decline of the water temperature from the initial set point to 285K before heating commenced and was taken to a maximum temperature of 314K before it started declining, on reaching to the lower set point of the thermometer the heating commenced again. Figure 10 and 11 showed the overview of the room and water temperature behaviour for second scenario which setup to run for 24 hours.

Table 4. Scenario one: The total amount of energy flow put into the system

Total energy used without Endotherm	Total energy used with Endotherm
104125000 Joules	93065000 Joules
Calculated percentage of energy saved with the use of Endotherm is 10.62%	

Table 5. Scenario two: The total amount of energy flow put into the system

Total energy used without Endotherm	Total energy used with Endotherm
986913620 Joules	749237120 Joules
Calculated percentage of energy saved with the use of Endotherm is 24%	

Results from the simulation gave power flows of the model (the rate of flow of heat into the water from the boiler) in units of watts, which was converted to energy by multiplying a unit of power by a unit of time and summing them up as shown in Table 1 and 2 for the scenarios performed.

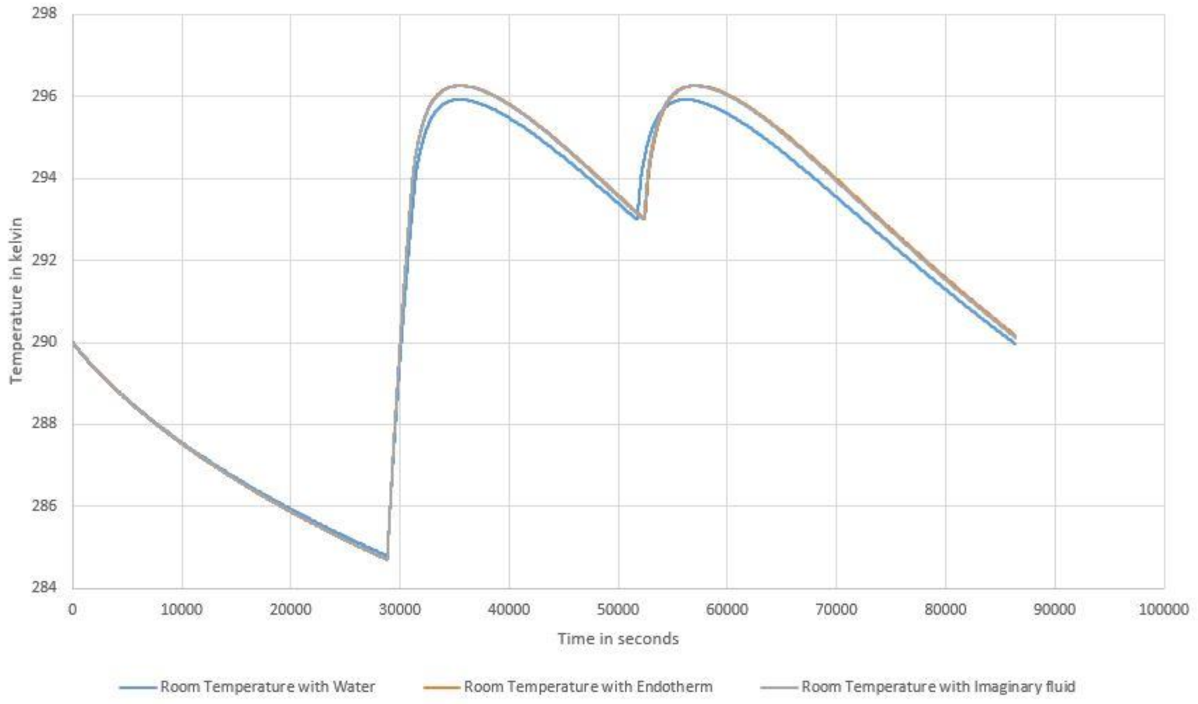

Figure 14. Scenario one: Effect of change in specific heat capacity in the simulated model

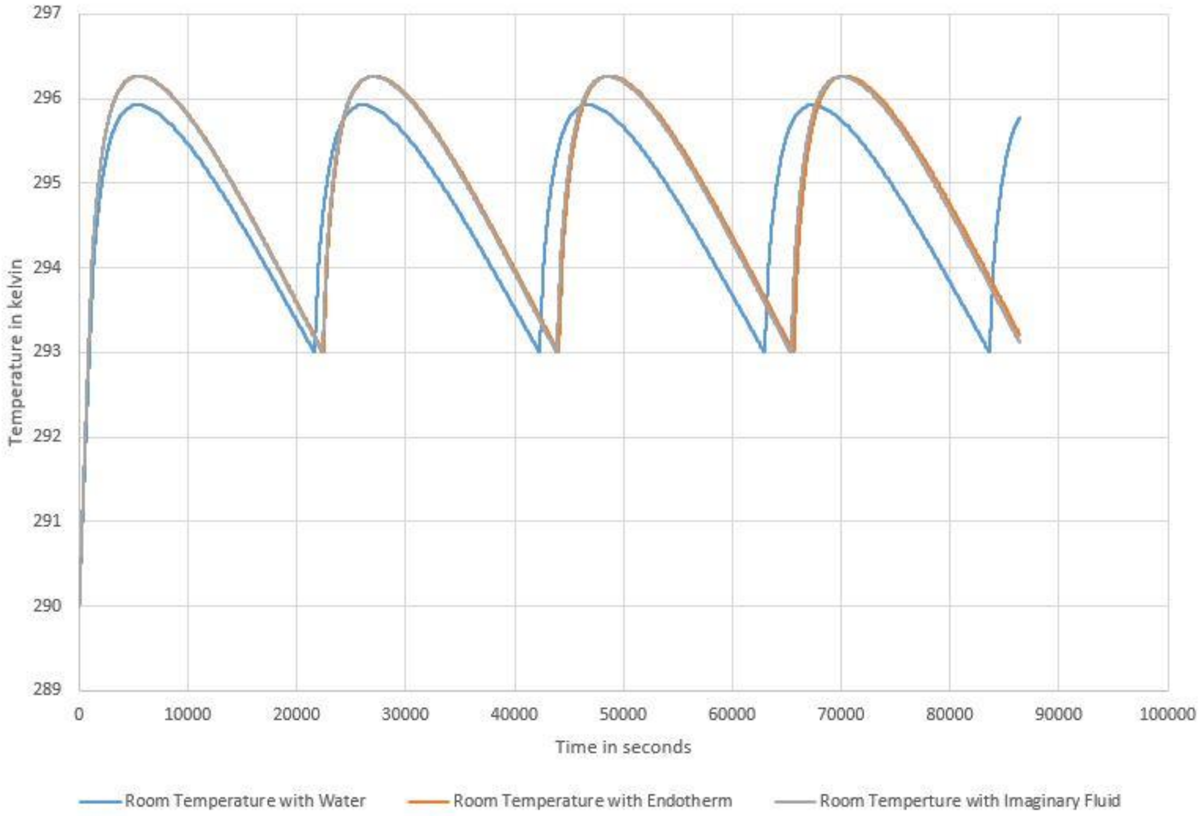

Figure 15. Scenario two: Effect of change in specific heat capacity in the simulated model

Figure and figure show an imaginary fluid created with the fluid properties of water specific heat capacity as the only exception as that of Endotherm was used in place to show the effect of a lower specific heat capacity on a heating system.

Table 6: Scenario one: Comparison of total energy used with the imaginary fluid result

Total energy used without Endotherm	Total energy used with Endotherm	Total energy used with the imaginary fluid
104125000 Mega joules	93065000 Mega joules	93378976 Mega joules

Table 7. Scenario two: Comparison of total energy used with the imaginary fluid result.

Total energy used without Endotherm	Total energy used with Endotherm	Total energy used with the imaginary fluid
104125000 Mega joules	93065000 Mega joules	93378976 Mega joules

4.3 Discussion: Simulation

Achieved results which were presented in the preceding chapter shows favourable impact on the outcome of installing endotherm in the heating system at Aston university. These results show some of the ways surfactant (non-ionic) can influence energy consumption.

From the simulation performed, the following observations were made which showed ways in which addition of Endotherm could influence heating system:

i. From scenario one after the room behaviour for water and endotherm was compared, the result showed that heating systems with endotherm will reach a maximum set room temperature faster than with water alone and the room temperature drops slower than with water alone in the system. Although when set at the same initial temperature before heating commenced, the result showed that temperature drop in the room with or without the addition of endotherm was the same.
ii. For the water temperature in scenario one, the result showed that endotherm will reach a maximum set water temperature quicker than with water alone as

a higher water temperature was achieved in the simulation with endotherm and also it will cool slower than water alone in the system.

iii. Room temperature behaviour in scenario two clearly showed the number of times the boiler cycled ON and OFF for the specified heating period to maintain temperature in the room, with water alone in the system the boiler had to operate four (4) cycles and with the addition of endotherm the boiler had to operate three (3) cycle. This showed a reduced frequency of the boiler coming ON/OFF which signifies less energy has been utilized.

Considering the results from the simulation it can be said that use of non-ionic surfactant specifically Endotherm will reduce energy usage, heat up the water in the boiler much quicker and get to a higher room temperature faster as compared to the use of water alone thereby making a heating system more responsive and efficient as shown in the considered scenarios. A closer look into the variation of the different fluid properties studied suggests the main reason for change in behaviour between the addition of endotherm and water alone in a heating system is in its specific heat capacity as endotherm has a lower specific capacity than water, this led me to perform additional simulation to check which of the fluid property is responsible for the results gotten. An imaginary fluid was created with the same fluid properties of water expect the specific heat capacity and that of Endotherm was used in place of it. The results of the room temperature behaviour and energy put into the system showed that in fact specific heat capacity is the dormant reason for improvements observed within the simulated system.

4.4 Result from Case Study Analysis

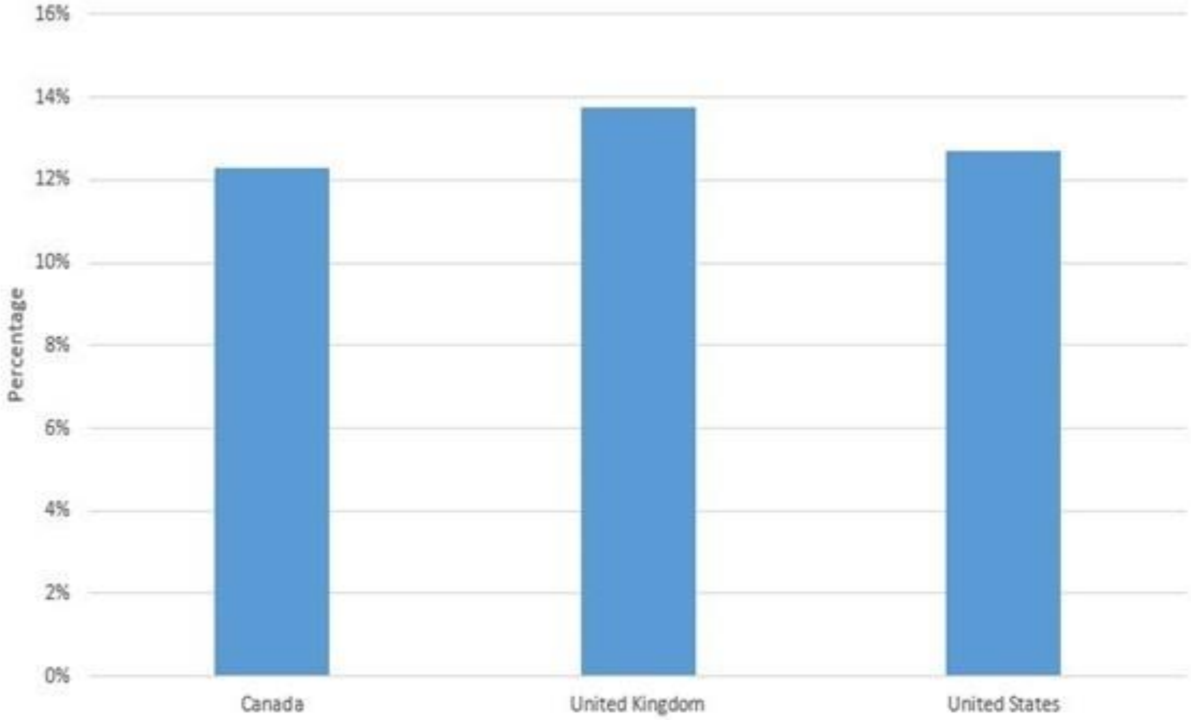

Figure 16. Cumulative average of energy savings achieved with all building types investigated in Canada, United States and United Kingdom.

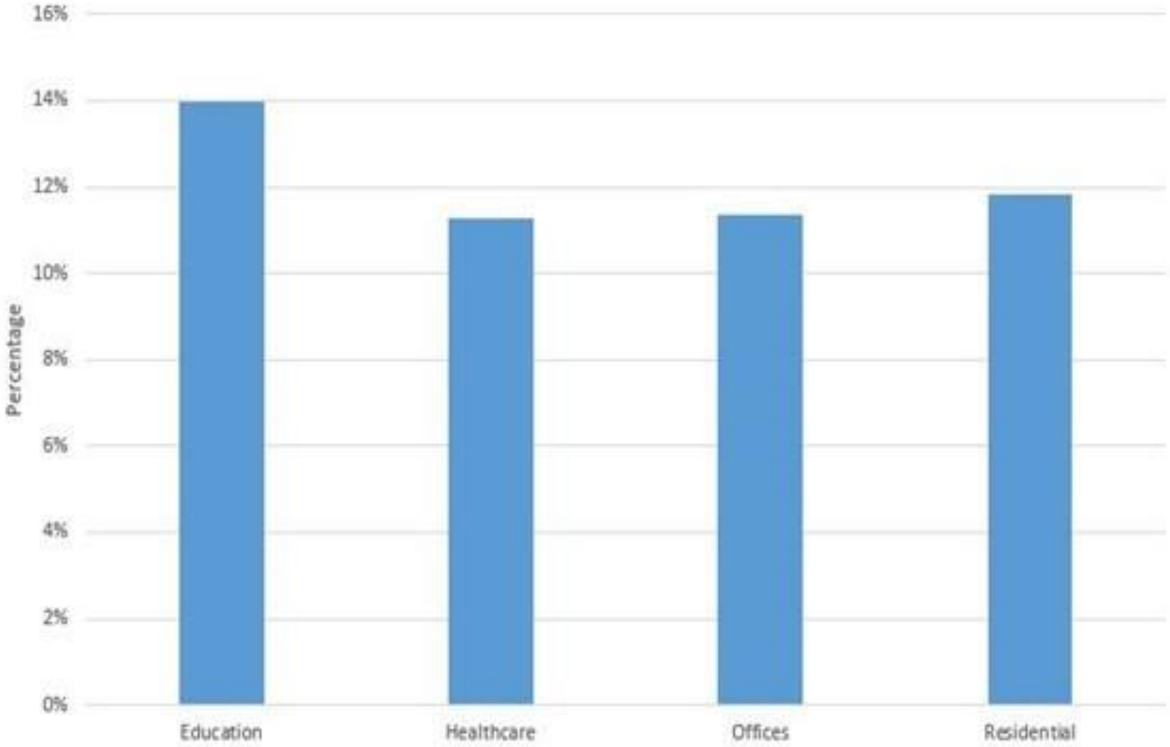

Figure 17. Cumulative average energy savings on various building types considered.

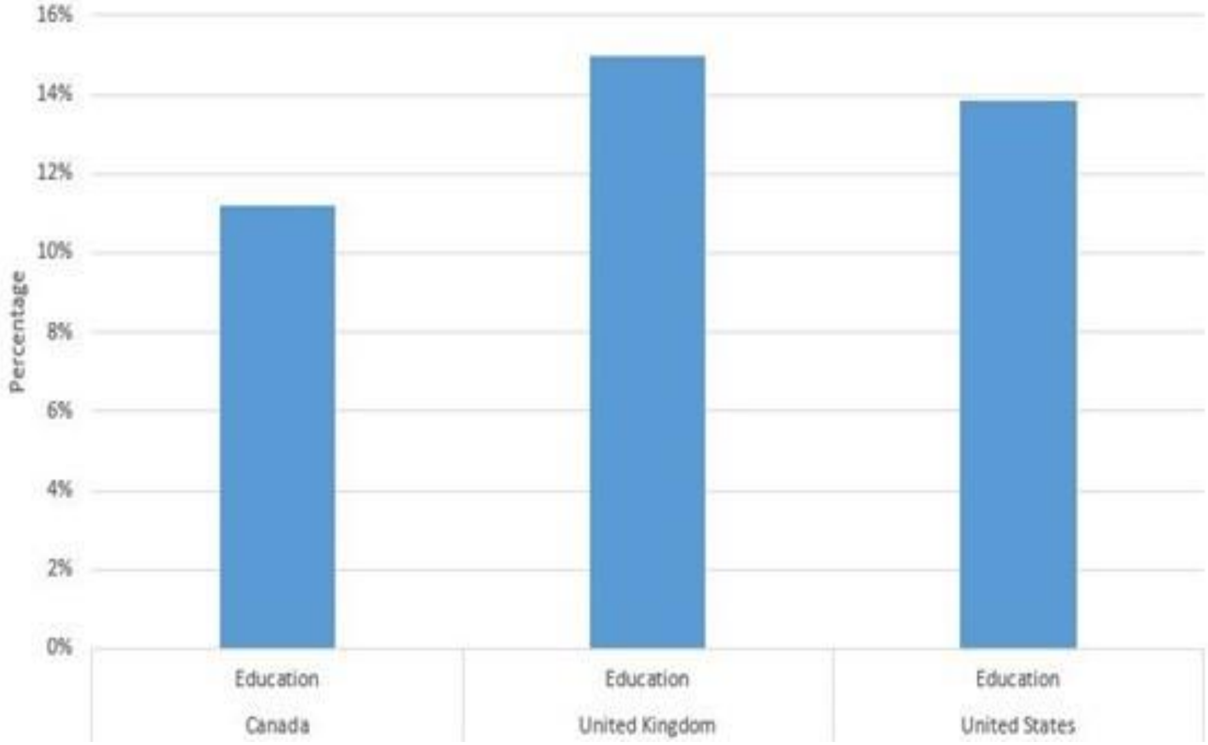

Figure 18. Average energy saving achieved on education building in Canada, United states, and United Kingdom

This figure shows the average energy saving when only education building type was considered across all identified countries.

Figure 16 shows the total summary of average energy savings achieved from countries the case studies has been performed, this summary only includes average savings of building that has met the selection criteria as discussed in the methodology section of this study. Figure 17 shows the total summary of average energy savings achieved according to the building types with all countries combined. Figure 18 shows the average energy saving when only education building type was considered across all identified countries.

Table 8 and 9 gives a range of saving with the minimum at 11% and the maximum at 15%, it also gives an idea of what could happen when Endotherm (non-ionic surfactant) is introduced in the heating system at Aston university main building.

Table 8. At 11% saving: Projected annual energy savings, financial and CO2e savings.

Aston University Building	Main Building ‘A’ Corner	Main Building ‘C’ Corner	Main Building ‘E’ Corner	Main Building ‘G’ Corner	North Wing	North Wing	TOTAL
Energy Savings (kWh) (11%):	176,000 kWh	176,000 kWh	176,000 kWh	176,000 kWh	121,000 kWh	121,000 kWh	946,000 kWh
Financial Savings (£) (11%):	£10,230	£10,230	£10,230	£10,230	£7,040	£7,040	£55000
CO2e Savings (kg) (11%):	38,016 kg	38,016 kg	38,016 kg	38,016 kg	26,136 kg	26,136 kg	204336 kg

Table 9. At 15% saving: Projected annual energy savings, financial and CO_2 savings

Aston University Building	Main Building ‘A’ Corner	Main Building ‘C’ Corner	Main Building ‘E’ Corner	Main Building ‘G’ Corner	North Wing	North Wing	TOTAL
Energy Savings (kWh) (15%):	240,000 kWh	240,000 kWh	240,000 kWh	240,000 kWh	165,000 kWh	165,000 kWh	1,290,000 kWh
Financial Savings (£) (15%):	£13,950	£13,950	£13,950	£13,950	£9,600	£9,600	£75000
CO_2 Savings (kg) (15%):	51,840 kg	51,840 kg	51,840 kg	51,840 kg	35,640 kg	35,640 kg	278640 kg

Table 9. At 15% saving: Projected annual energy savings, financial and CO_2 savings

4.5 Discussion: Case Study Analysis

Achieved results which were presented in the results sections shows positive potential of what might happen installing endotherm at Aston university heating system. These results show up to a possible range of 11 to 15% energy saving, CO_2 reduction and financial savings.

From the study and statistical analysis carried out, the following observations were made which might influence the variations in results:

i. Climate zone/climatic conditions of the countries studied has a huge influence on the heating degree days (HDD) used for the improved efficiency calculations. It is worthy to mention the measurement called a heating degree day is used to determine how much energy is required to heat a structure. Temperature readings of the outside air are used to calculate HDD. The number of HDD at a particular place is thought to be directly related to the heating requirements for a given building at that location. So, the different heat degree days according to the country/location at the time the readings were taken will have an influence the result as lower heating degree days will demand more energy in order to heat up a building to a certain temperature as compared to a higher heating degree day.

ii. Building usage, different building types identified has different usage/occupancy behaviour which will have an influence on the energy saving percentage calculated. For instance, it was observed that the coronavirus disease (COVID-19) epidemic had a substantial impact on occupancy and consequently demand of numerous buildings.

iii. The International Protocol for the Measurement and Verification of Performance (IPMVP) Option C, which employs total natural gas usage, serves as the basis for the standard approach for an EndoTherm pilot project. According to Efficiency Valuation Organization (EVO) the International Performance Measurement and Verification Protocol specifies standard terminology, offers best practises, and encourages increased investment in energy and water efficiency, demand management, and renewable energy projects in order to quantify the results of such investments (EVO, 2022). The requirement for a standard process to confirm savings reported by Energy Service Companies (ESCOs) implementing Energy Conservation Measures (ECM) was a significant motivating factor. The protocol offers a foundation for figuring out how much water and energy ECMs save. Although while reviewing one of the identified case studies performed on an office building in the United Kingdom, application of the IPMVP methodology was not observed which might have an influence on the result.

iv. Various heating system configurations were observed in each case study, such as different number of boilers and sizes this could also influence the percentage savings obtained.

v. There was no fixed duration for all the post endotherm study carried out on the identified buildings which might influence the energy savings considering the effect of HDD.

Based on the case study analysis I got numbers ranging from 11 to 15% for education type buildings, therefore the saving at Aston University might be between 11 to 15%. On applying the lower and upper value of percentage saving gotten, the result showed what might happen if Endotherm (non-ionic surfactant) is introduced in the heating system at Aston University. A possible energy saving, reduction of greenhouse gas emission (CO_2) and financial saving of up to 15% is likely to be achieved.

The implication of this research shows that Aston university could benefit from installing a non-ionic surfactant in its heating system and highting the effect of change of fluid properties on heating system performance.

Limitation of this research approach is the case study analysis has a small sample size and was performed on different buildings; the results may not apply to the identified exemplar building at Aston university. The usage of software simulations has advantages and disadvantages because it allows people to make mistakes that would be extremely difficult to correct in a real lab, which boosts their confidence to try again by erasing them with the simple click of a button. It also encourages them to take chances that they might not otherwise take. But by eliminating the physical element, it also diminishes the magnificence of bringing an idea to life. Unavailability of data/resources was the main limitation I had using this approach.

4.6 Future Work

If I had longer time to continue this project, the next logical would be;

For the case study method, a more in-depth statistical analysis can be performed on each case study if the raw data can be made available, in other to validate the regression line gotten “from the historical consumption normalised against heating degree days for the same period” and validate the total efficiency improvement over the given pilot period.

For the simulation method, an attempt to simulate the whole building or map out rooms with different characteristic as room with similar characteristics will give the same room result. Also mimicking of the heat exchanger as given in the BMS page would enable me to predict a more tailored/accurate result of the effect of installing the specified non-ionic surfactant into the heating system at Aston University main building. I would also like to spend a good amount of time looking at what the simulated model is doing and what is not doing as compared to a real-world building, considering internal heat generation and the occupant behaviour as well.

5 CONCLUSION AND RECOMMENDATION

5.1 Overview

This chapter highlights the concluding remarks and recommendations.

5.2 Conclusion

The possible effects of the use of a specific non-ionic surfactant in the building heating system at Aston university were investigated. Analysis of the published case study data that is most relevant to Aston University showed potential savings of 11 to 15% after the case study analysis for buildings similar to the exemplar building at Aston University, the results also showed the expected energy, emission and cost saving at the maximum and minimum range of the values. The simulation showed some of the ways by which the specified non-ionic surfactant can influence energy consumption in a heating system with the result showing a 10.62% energy saving for a 10-hour runtime/scenario and a 24% energy saving for a 24-hour runtime/scenario; Endotherm showed to be more responsive/efficient than water alone in a heating system as it is quicker to reach a set maximum water temperature in a boiler and cools slower than water alone for the specific scenarios performed. The results also showed it is also faster getting to a set maximum room temperature and a slower room temperature drop hence reducing the boiler cycle than using water alone in a heating system. Almost all these results can be attributed to the lower specific heat capacity of endotherm than that of water as shown. Therefore, the answer to the research question of this study is that the low heat capacity changes the thermal behaviour of the building in favour of lower energy consumption which in turn reduces CO_2 emission and also drive down running costs.

5.3 Recommendation

Future studies should further explore the challenge of heat transfer reduction in heat exchangers when surfactants are introduced in a heating system as this creates a lot of bias on use and implementation of environmentally friendly surfactants.

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APPENDIX

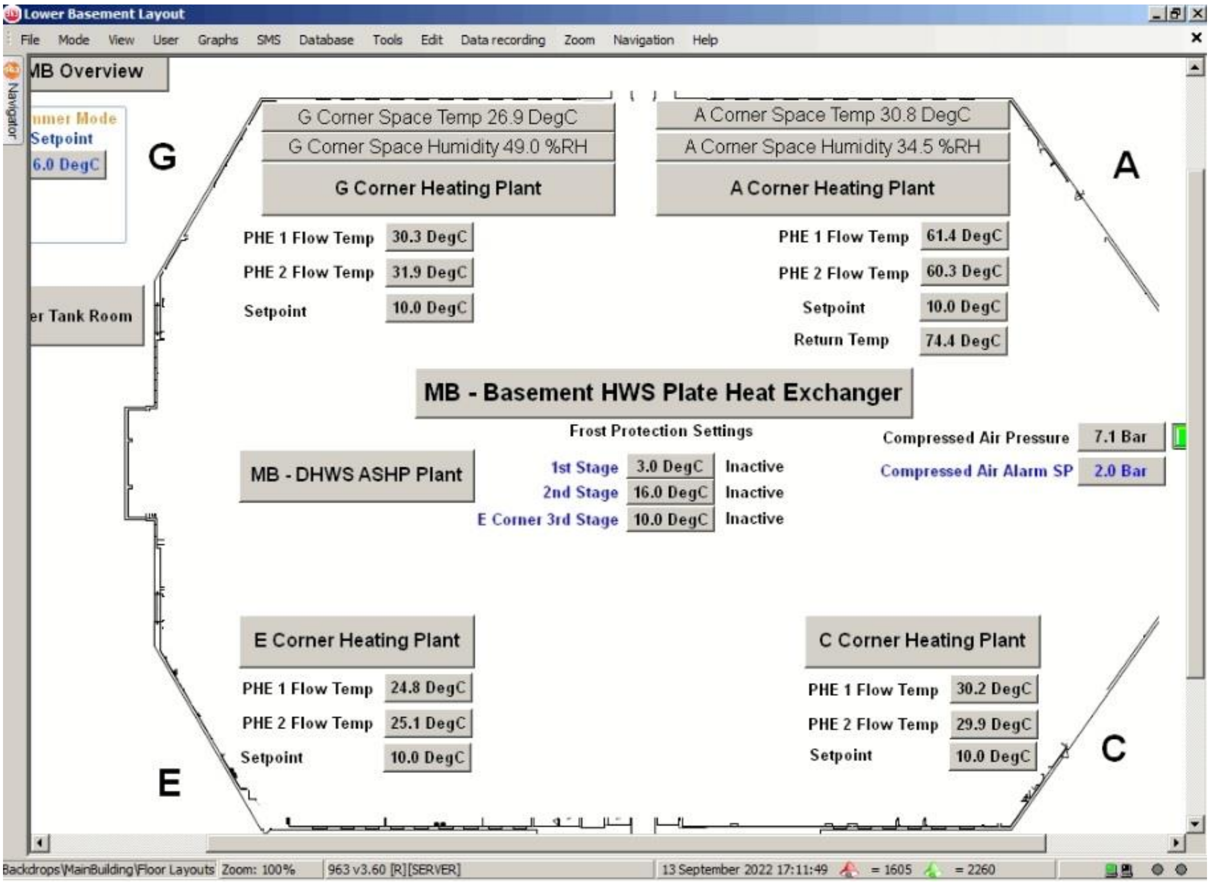
Appendix A

Aston University Main Building Heating System

The main building heating is fed from the district heating from the main boiler house.

There are 4 x plate heat exchangers that modulate the heating flow temperature based on the outside air temperature once the district heating has been fed into the main building. A 3-port valve actuator controls the variable temperature circuit in this system.

The layout of the 4 corners can be seen in figure 19



mmer Mode
Setpoint 6.0 DegC

G Corner Space Temp 26.9 DegC
G Corner Space Humidity 49.0 %RH
A Corner Space Temp 30.8 DegC
A Corner Space Humidity 34.5 %RH

G Corner Heating Plant	
PHE 1 Flow Temp	30.3 DegC
PHE 2 Flow Temp	31.9 DegC
Setpoint	10.0 DegC

A Corner Heating Plant	
PHE 1 Flow Temp	61.4 DegC
PHE 2 Flow Temp	60.3 DegC
Setpoint	10.0 DegC
Return Temp	74.4 DegC

Frost Protection Settings		
1st Stage	3.0 DegC	Inactive
2nd Stage	16.0 DegC	Inactive
E Corner 3rd Stage	10.0 DegC	Inactive

Compressed Air Pressure 7.1 Bar
Compressed Air Alarm SP 2.0 Bar

E Corner Heating Plant	
PHE 1 Flow Temp	24.8 DegC
PHE 2 Flow Temp	25.1 DegC
Setpoint	10.0 DegC

C Corner Heating Plant	
PHE 1 Flow Temp	30.2 DegC
PHE 2 Flow Temp	29.9 DegC
Setpoint	10.0 DegC

Backdrops\MainBuilding\Floor Layouts Zoom: 100% 963 v3.60 [R][SERVER] 13 September 2022 17:11:49 = 1605 = 2260

Figure 19. Screenshot of the BSM at Aston University main building

A screenshot of the trend building management system is seen here. A trend outstation is present at each of the four corners, and it is connected to the ethernet infrastructure. Trend drives the motorised valve actuator into a position to the estimated setpoint to regulate the flow's temperature.

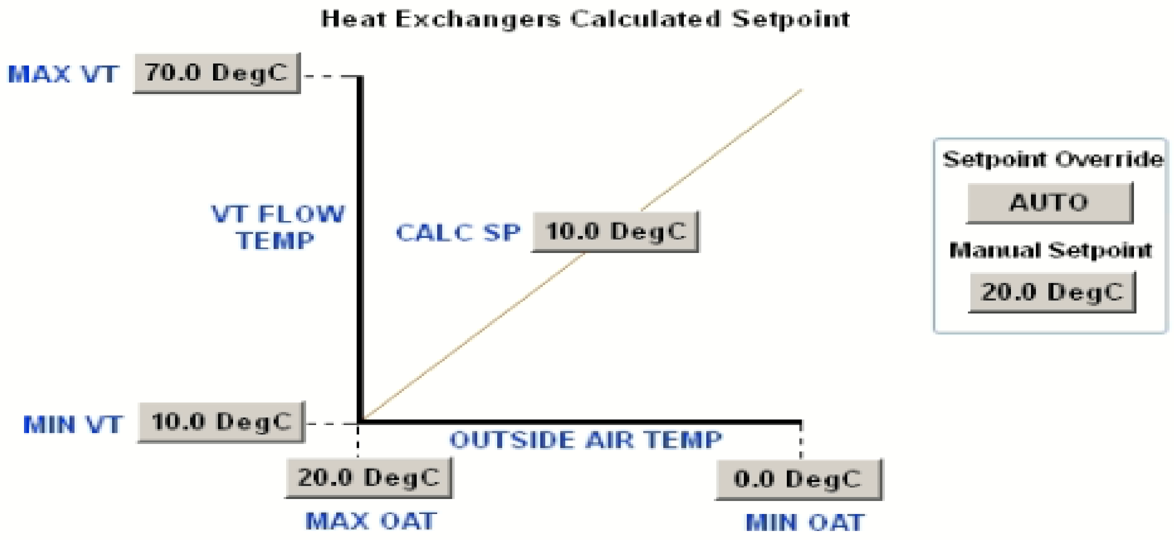
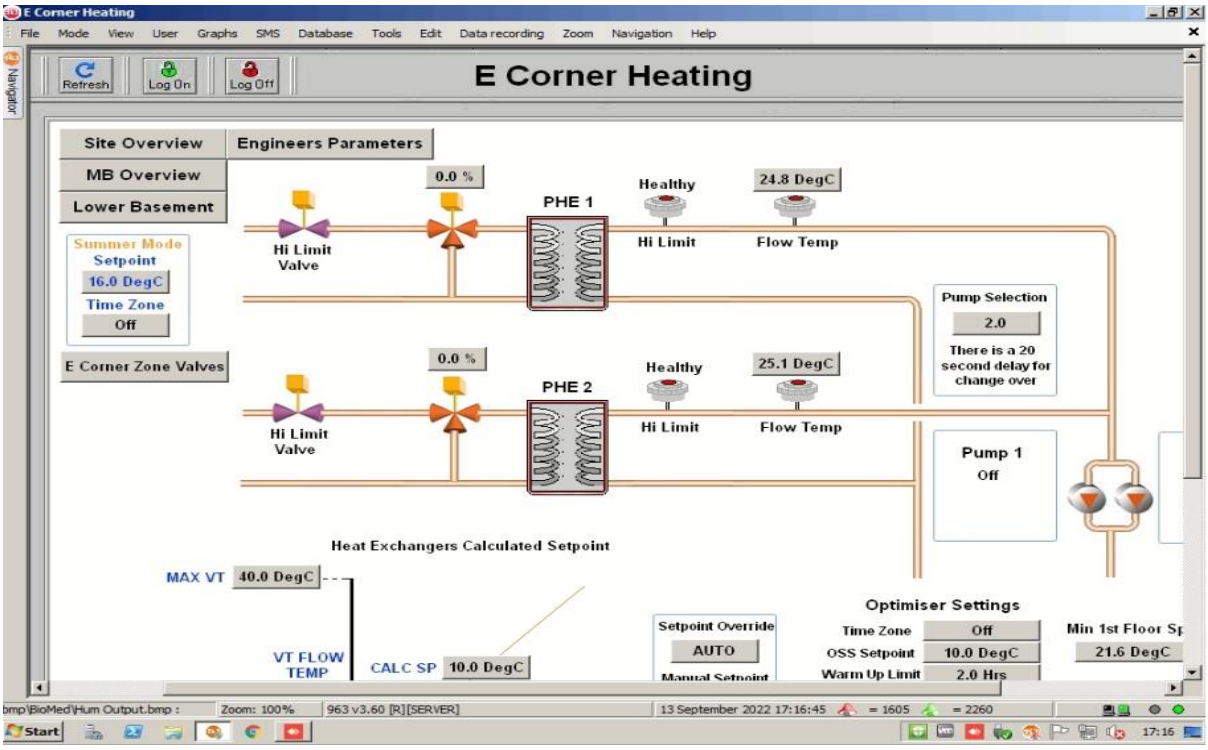


Figure 20. Heat exchangers calculated setpoint

The front-end supervisor can fully alter all of these parameters to accommodate changing weather conditions. As a result, it can be altered during the summer much as the winter setpoints.

Additionally, a summer interlock prevents the pumps and valve from operating if the ambient temperature rises beyond 16 degrees Celsius. Upon occupancy, a time zone/optimiser turns on/off the pumps.



Summer Mode Setpoint 16.0 DegC
Time Zone Off

0.0 %

24.8 DegC

0.0 %

25.1 DegC

Pump Selection 2.0

There is a 20 second delay for change over

Pump 1 Off

MAX VT 40.0 DegC

CALC SP 10.0 DegC

Setpoint Override AUTO

Manual Setpoint

Time Zone Off

OSS Setpoint 10.0 DegC

Warm Up Limit 2.0 Hrs

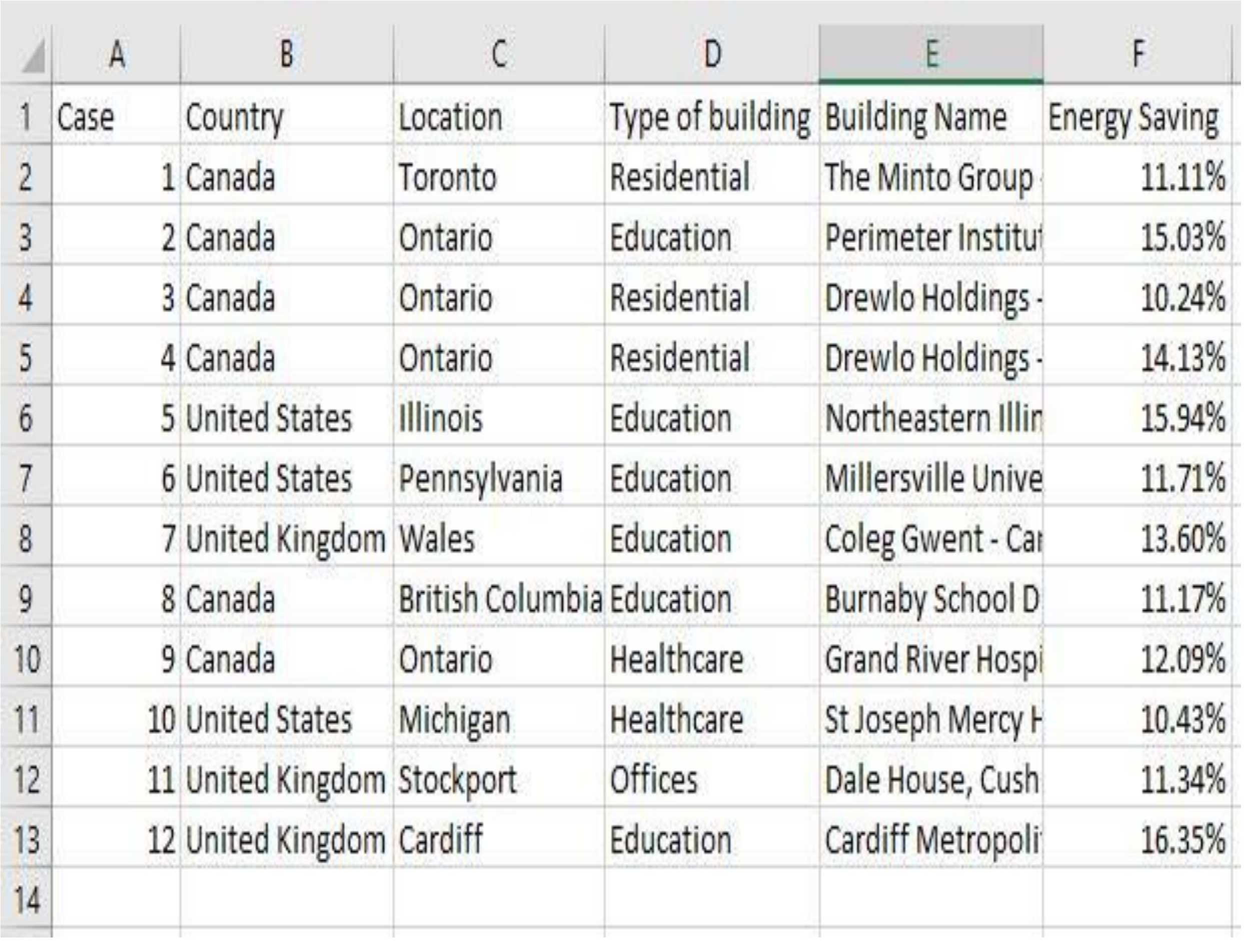
Min 1st Floor Sp 21.6 DegC

bmp\BioMed\Hum Output.bmp : Zoom: 100% 963 v3.60 [R][SERVER] 13 September 2022 17:16:45 = 1605 = 2260

17:16

Figure 21. E Corner Heating

Appendix B



	A	B	C	D	E	F
1	Case	Country	Location	Type of building	Building Name	Energy Saving
2	1	Canada	Toronto	Residential	The Minto Group	11.11%
3	2	Canada	Ontario	Education	Perimeter Institu	15.03%
4	3	Canada	Ontario	Residential	Drewlo Holdings -	10.24%
5	4	Canada	Ontario	Residential	Drewlo Holdings -	14.13%
6	5	United States	Illinois	Education	Northeastern Illin	15.94%
7	6	United States	Pennsylvania	Education	Millersville Unive	11.71%
8	7	United Kingdom	Wales	Education	Coleg Gwent - Ca	13.60%
9	8	Canada	British Columbia	Education	Burnaby School D	11.17%
10	9	Canada	Ontario	Healthcare	Grand River Hospi	12.09%
11	10	United States	Michigan	Healthcare	St Joseph Mercy	10.43%
12	11	United Kingdom	Stockport	Offices	Dale House, Cush	11.34%
13	12	United Kingdom	Cardiff	Education	Cardiff Metropoli	16.35%
14						

Figure 22. List and details of the case studies analysed

Appendix C

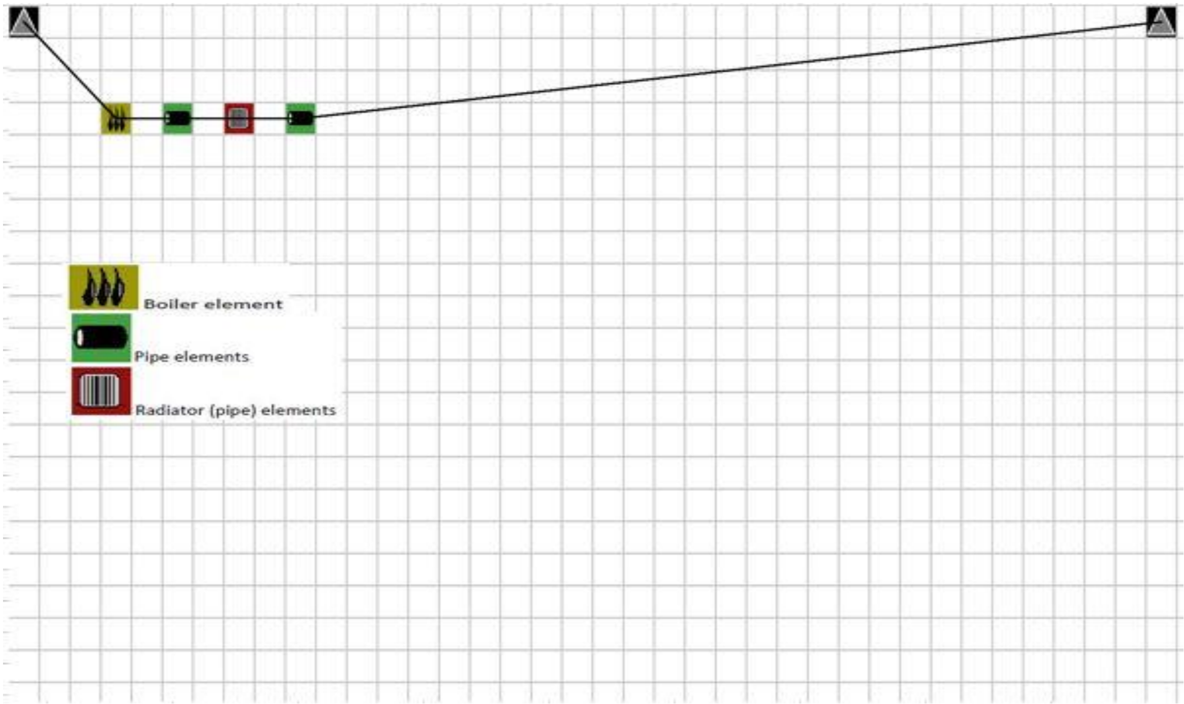
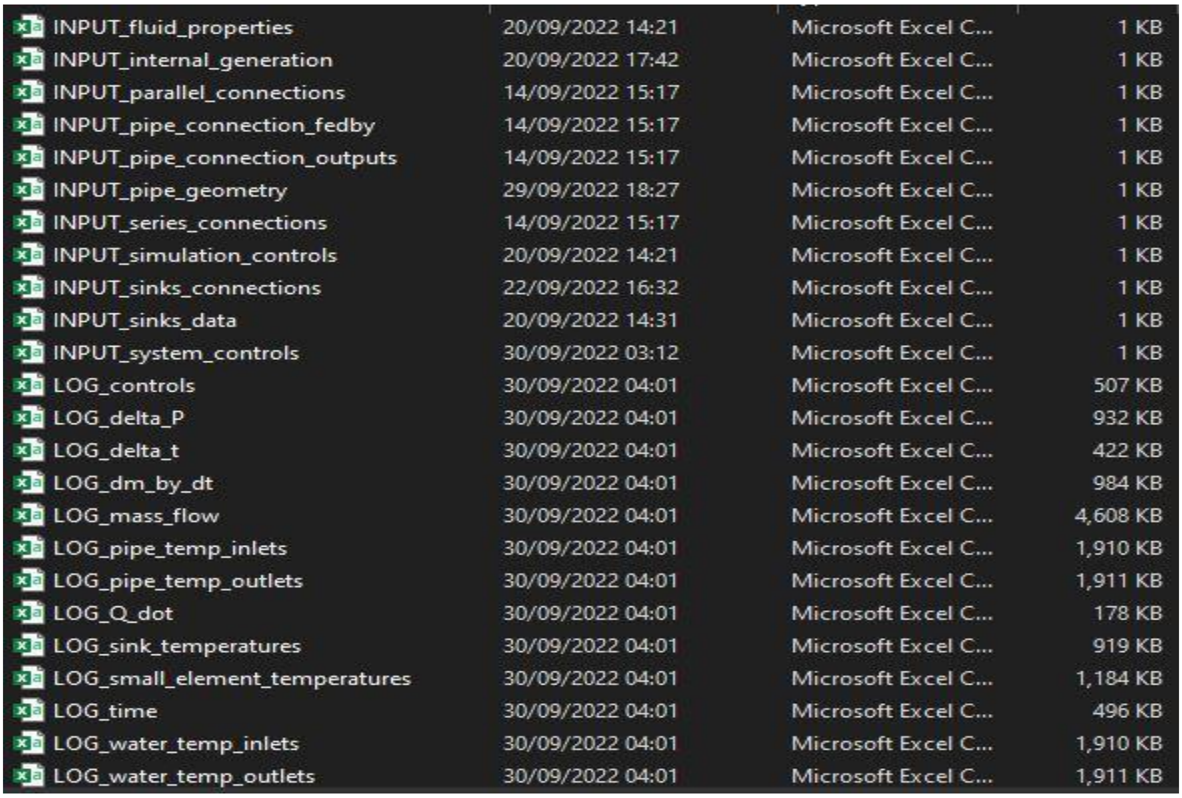


Figure 23. The simulated model canvas from the software

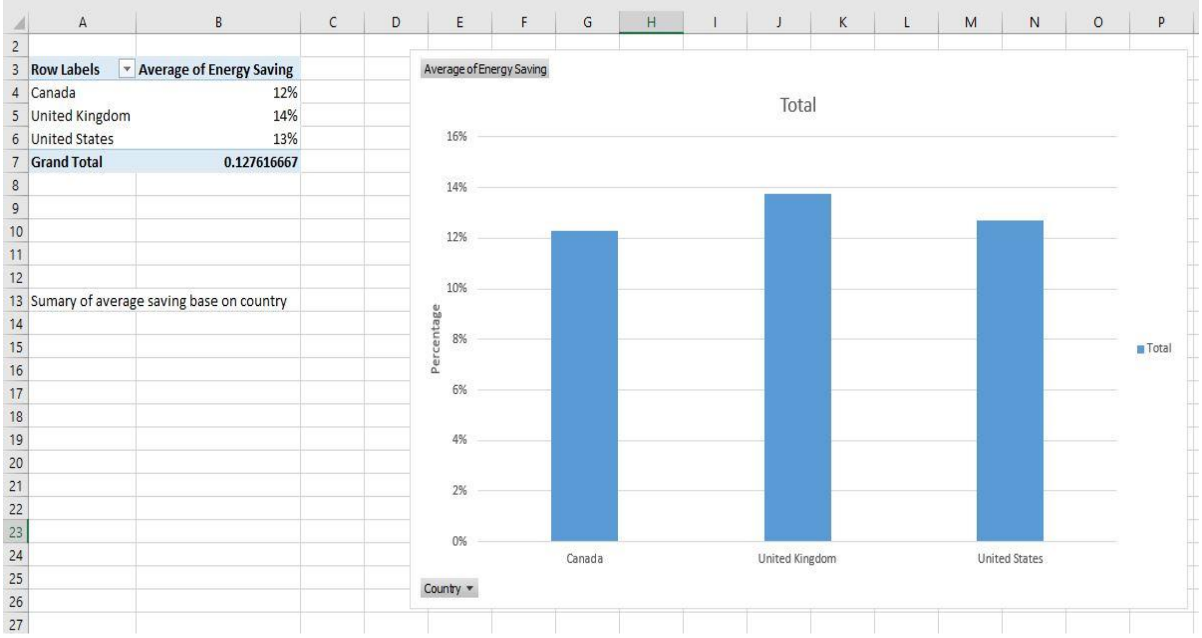


INPUT_fluid_properties	20/09/2022 14:21	Microsoft Excel C...	1 KB
INPUT_internal_generation	20/09/2022 17:42	Microsoft Excel C...	1 KB
INPUT_parallel_connections	14/09/2022 15:17	Microsoft Excel C...	1 KB
INPUT_pipe_connection_fedby	14/09/2022 15:17	Microsoft Excel C...	1 KB
INPUT_pipe_connection_outputs	14/09/2022 15:17	Microsoft Excel C...	1 KB
INPUT_pipe_geometry	29/09/2022 18:27	Microsoft Excel C...	1 KB
INPUT_series_connections	14/09/2022 15:17	Microsoft Excel C...	1 KB
INPUT_simulation_controls	20/09/2022 14:21	Microsoft Excel C...	1 KB
INPUT_sinks_connections	22/09/2022 16:32	Microsoft Excel C...	1 KB
INPUT_sinks_data	20/09/2022 14:31	Microsoft Excel C...	1 KB
INPUT_system_controls	30/09/2022 03:12	Microsoft Excel C...	1 KB
LOG_controls	30/09/2022 04:01	Microsoft Excel C...	507 KB
LOG_delta_P	30/09/2022 04:01	Microsoft Excel C...	932 KB
LOG_delta_t	30/09/2022 04:01	Microsoft Excel C...	422 KB
LOG_dm_by_dt	30/09/2022 04:01	Microsoft Excel C...	984 KB
LOG_mass_flow	30/09/2022 04:01	Microsoft Excel C...	4,608 KB
LOG_pipe_temp_inlets	30/09/2022 04:01	Microsoft Excel C...	1,910 KB
LOG_pipe_temp_outlets	30/09/2022 04:01	Microsoft Excel C...	1,911 KB
LOG_Q_dot	30/09/2022 04:01	Microsoft Excel C...	178 KB
LOG_sink_temperatures	30/09/2022 04:01	Microsoft Excel C...	919 KB
LOG_small_element_temperatures	30/09/2022 04:01	Microsoft Excel C...	1,184 KB
LOG_time	30/09/2022 04:01	Microsoft Excel C...	496 KB
LOG_water_temp_inlets	30/09/2022 04:01	Microsoft Excel C...	1,910 KB
LOG_water_temp_outlets	30/09/2022 04:01	Microsoft Excel C...	1,911 KB

Figure 24. Data input and output of the simulation software

Appendix D

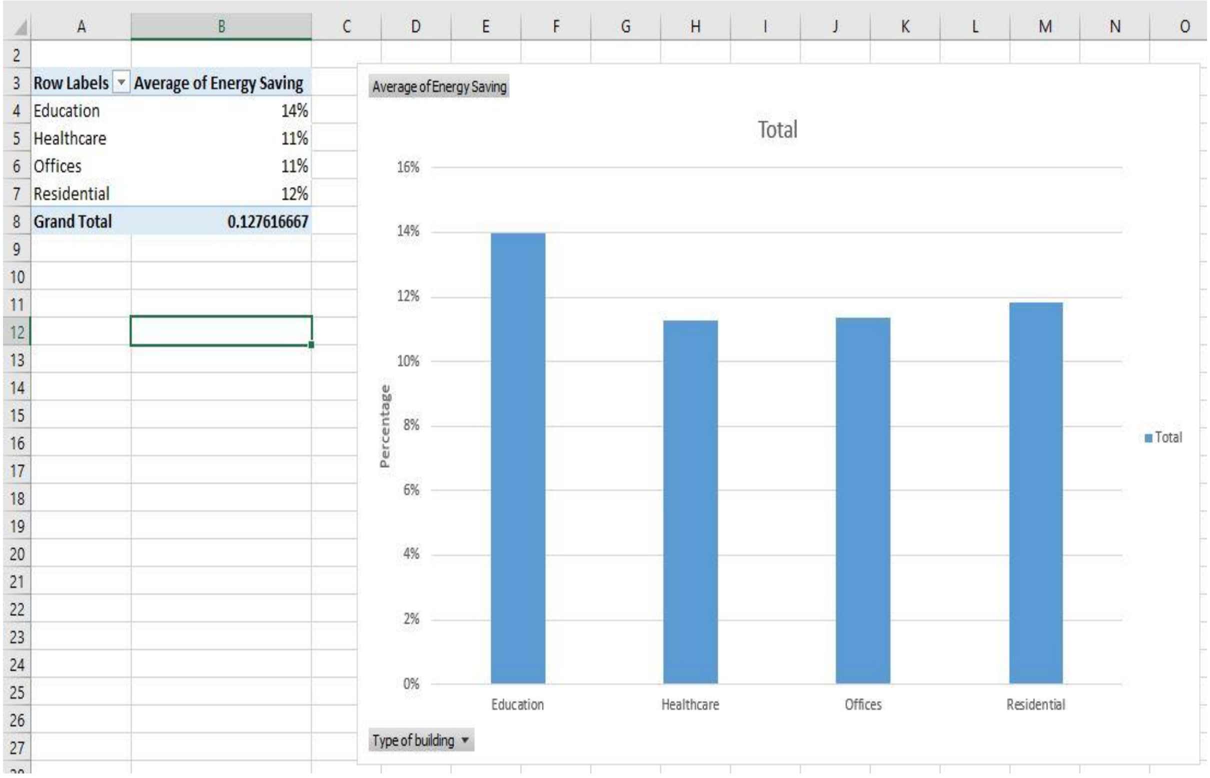
Computer program built using Microsoft excel to execute the case study analysis



Row Labels	Average of Energy Saving
Canada	12%
United Kingdom	14%
United States	13%
Grand Total	**0.127616667**

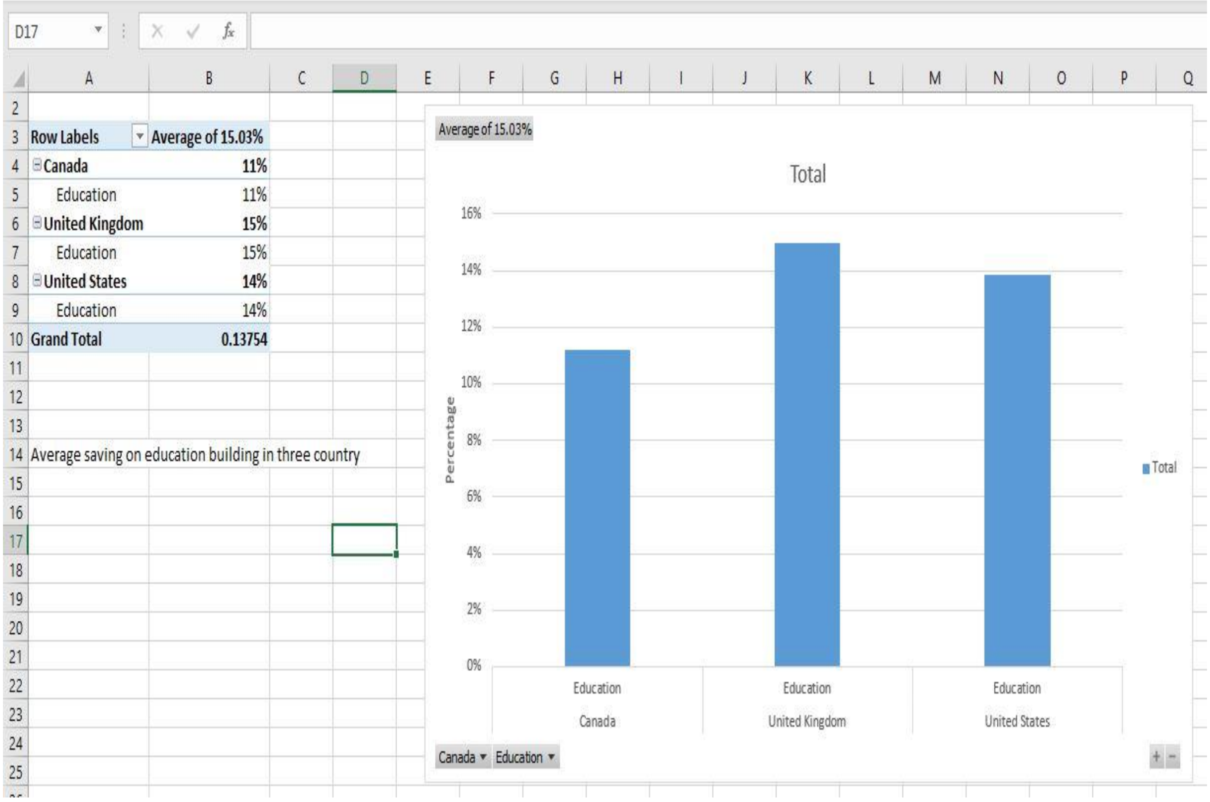
Sumary of average saving base on country

Figure 25. Computer program for the analysis of the cumulative average of energy savings achieved with all building types investigated in Canada, United States and United Kingdom



Row Labels	Average of Energy Saving
Education	14%
Healthcare	11%
Offices	11%
Residential	12%
Grand Total	**0.127616667**

Figure 26. Computer program for cumulative average energy savings on various building types considered



Row Labels	Average of 15.03%
Canada	**11%**
Education	11%
United Kingdom	**15%**
Education	15%
United States	**14%**
Education	14%
Grand Total	**0.13754**

Average saving on education building in three country

Figure 27. Computer program for average energy saving achieved on education building in Canada, United states, and United Kingdom