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**Numerical and Experimental Investigation on energy saving using
individual space chilled water flow control**

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Abstract

Chilled water plants represent a significant component of energy consumption in institutional buildings, where efficient operation is critical to reducing operational costs and environmental impact. This research investigates the potential energy savings and performance improvements achievable through the implementation of a predictive-adaptive chilled water flow control strategy in the chilled water system of the University of Nottingham Malaysia, with a detailed focus on Block B, a representative office building. An integrated detailed numerical model coupling building thermal dynamics with chilled water plant operation was developed and rigorously validated against experimental data collected from a scaled prototype Heating, Ventilation, and Air Conditioning facility. Two flow control strategies were analysed: the conventional constant flow control currently employed and the proposed predictive-adaptive control, which dynamically adjusts chilled water flow rates based on real-time thermal loads at individual zones. Results demonstrated that the predictive-adaptive strategy significantly outperformed the constant flow approach, achieving approximately 46% reduction in chilled water consumption and 54% reduction in total energy use. Thermal comfort compliance improved significantly, with indoor temperatures maintained within the acceptable comfort range for about 85% of operational hours under the adaptive control, compared to only 21% under constant flow. The adaptive system further enhanced chiller efficiency through better load matching and reduced pumping energy, contributing to substantial carbon emissions reduction. The findings highlight the critical role of intelligent flow control in optimizing chilled water plant performance, offering a viable pathway to enhance energy efficiency, occupant comfort, and environmental sustainability in large-scale building cooling systems. Limitations of the study include the focus on a single building in a tropical climate and assumptions inherent in the modelling approach. Future research is recommended to explore

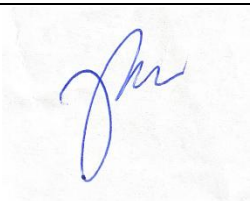
the applicability of predictive-adaptive flow control across diverse climates and building types, integrate advanced machine learning algorithms, and evaluate long-term field performance. This study provides valuable insights and practical recommendations for the design, control, and operation of chilled water systems, supporting institutional efforts to reduce energy consumption and greenhouse gas emissions in building operations.

Declaration

I hereby declare that the work presented in this thesis has not been submitted for any other degree or professional qualification and that it is the result of my independent work.

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Signature



Date 5/5/2025

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List of Abbreviations

HVAC	Heating, Ventilation, and Air Conditioning
CHW	Chilled Water
FCU	Fan Coil Unit
AHU	Air Handling Unit
VSD	Variable Speed Drive
CF1	Coefficient Factor 1
CF2	Coefficient Factor 2
VCHW	Volume Flow Rate of Chilled Water
VFD	Variable Frequency Drive
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
kW	Kilowatt
kWh	Kilowatt-hour
GPM	Gallons Per Minute
PID	Proportional-Integral-Derivative
BMS	Building Management System
IoT	Internet of Things
CFD	Computational Fluid Dynamics

CAV	Constant Air Volume
VAV	Variable Air Volume
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
RTU	Rooftop Unit

List of Symbol

Delta-T	Delta Temperature
Mdot	Mass Flow Rate
$\dot{M}_{air-AHU-B1}$	Mass Flow Rate of Air in AHU B1
$\dot{M}_{CHW-AHU-B1}$	Flow Rate of Chilled Water in AHU B1
M_{rated}	Rated Mass Flow Rate
DT_{max}	Maximum Allowable Delta Temperature
$DT_{max\ CHW}$	Maximum Delta Temperature for Chilled Water
QFCB1	Cooling Load of Fan Coil Unit B1
QCGFZ4	Cooling Load of Central Zone Fan Z4
y_s	Schedule
$y_{pump\ AHU-B1}$	Pump Power of AHU B1 signal
PCHW	Chilled Water Pump Power
$T_{air_{in}}$	Incoming Air Temperature
$T_{air_{out}}$	Outgoing Air Temperature
$T_{CHW_{in}}$	Incoming Chilled Water Temperature
$T_{CHW_{out}}$	Outgoing Chilled Water Temperature
$\Delta PCHW$	Pressure Drop in Chilled Water System

Chapter 1: Introduction

1.1 Background of study

Chilled water plants are extensively utilised for building cooling and constitute a substantial portion of a facility's energy expenditure. Given that chillers account for the predominant energy consumption in chilled water plants, it is essential to guarantee their optimal operation. In evaluating the operation of plants and chillers, a critical component to examine is the temperature difference between the return and supply chilled water. The temperature variation will be designated as delta-T. When the delta-T significantly decreases below the design level under specific conditions, this phenomenon is referred to as low delta-T syndrome. Low delta-T syndrome impacts many facilities and typically occurs during periods of reduced cooling demands. Minimising or avoiding low delta-T in chillers and plants is crucial, since it leads to decreased efficiency and wasted energy due to heightened chiller energy consumption and pumping power. This thesis specifically examines the chilled water plant at Nottingham University Malaysia. This plant operates as a primary-secondary system and consists of four blocks[1].

According to the Department of Statistics Malaysia (DOSM), Malaysia recorded a Gross Domestic Product (GDP) of RM1.93 trillion in 2024, reflecting a real GDP growth of 5.1% year-on-year [2]. The population was 32.7 million in 2022 and is projected to reach 40 million by 2050. In 2020, the urbanisation rate was 75% and is projected to attain 85% by 2040. Economic and demographic expansion, alongside swift urbanisation, will propel an increase in energy demand, anticipated to rise by 2% per annum until 2050[3]. The residential and commercial sectors constitute a significant portion of energy consumption, accounting for around 14% of the nation's overall energy use in 2020[4,5]. The construction sector accounts

for around 20% to 60% of overall energy consumption throughout various regions of the world [6–8]. Energy consumption in office buildings primarily involves heating, cooling, lighting, and the operation of computers and printers. Ihara and Gustavsen analysed and established that heating and cooling energy consumption accounts for approximately 45% of the total energy usage in office buildings in Japan[9]. Pérez-Lombard and Ortiz indicated that HVAC systems consume approximately 50% of energy in non-residential structures In Malaysia [10]. For tropical and humid conditions, air conditioning is vital for occupant comfort in buildings. Air-cooled devices can effectively cool small spaces; however, in larger structures, the cooling capacity may increase tenfold. The expense of an air-cooled unit with such substantial cooling capacity is prohibitive; hence, chillers are utilised to provide greater cooling capacity at a reduced cost. Chiller systems are essential components of HVAC systems, historically utilised for cooling through centralised air conditioning. There are primarily two categories of chillers: air-cooled and water-cooled. The distinction between the two categories fundamentally dictates the method of heat rejection from the system. Water-cooled chillers have superior efficiency and extend operational lifespan compared to their air-cooled counterparts, as they utilise water to dissipate heat from the system, which possesses a higher specific heat capacity than air [11]. Consequently, our primary focus will be on water-cooled chillers that utilise a cooling tower for heat rejection from water. Conventional water-cooled chillers consist of three primary cycles: the refrigeration cycle, the cooling water loop, and the chilled water loop. The entire system operates cohesively as a unit under the vapour compression cycle, utilising refrigerant as the working fluid.

Although chilled water systems are novel to many, the principle has existed since ancient Roman times. Ancient civilizations, including the Romans, Egyptians, and Persians, developed passive cooling techniques using water and airflow. These included water channels, fountains,

and wall-integrated systems to cool interiors through evaporative and conductive effects [12]. In 1926, Carrier developed the inaugural centrifugal chiller, enabling large-scale air cooling for buildings. Since that time, chillers have experienced significant innovation, resulting in a variety of forms. The fundamental function of a chiller is to extract heat from water. A chilled water system is commonly located in medium to large buildings and comprises plant equipment that provide cooling for the structure. Chilled water systems are uncommon in residential buildings, although they are extensively utilised in commercial and industrial structures. Chillers employed in the industry to regulate the cooling of mechanisms, processes, goods, or machinery. Industrial chillers serve various sectors, including food and beverage processing, manufacturing, and the semiconductor industry. Consequently, the need of optimising a chiller system to conserve energy and reduce costs must be emphasised to deliver superior solutions for air conditioning and industrial requirements. Cooling is predominantly accomplished using a chilled water system in substantial edifices such as hotels, hospitals, and airports. Chilled water systems are utilised to cool high-heat areas, including data centres, server farms, and various industrial operations and gear. Unlike air conditioning systems that depend on substantial quantities of refrigerant chemicals, a water-cooled chiller system utilises cooling water to disperse coolness and expel heat from the structure. Chilled water systems vary in size and complexity to fit the structure or purpose. A basic water chiller schematic is shown in Figure 1.1.

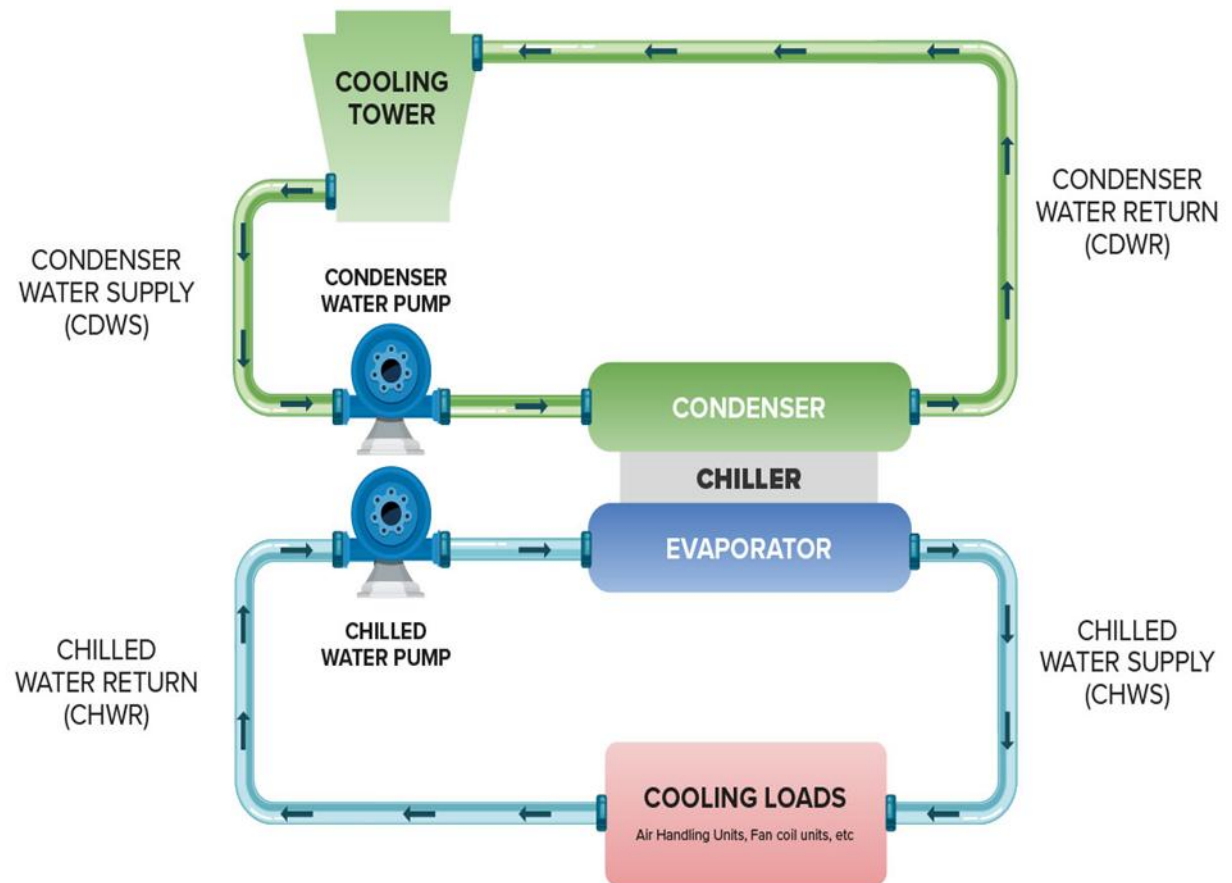


Figure 1.1 Simple schematic diagram of a water chiller system

The basic water-cooled chiller as shown in Figure 1.1 operates by circulating water through two major loops: the condenser water loop and the chilled water loop. In the condenser loop, warm condenser water is pumped from the chiller's condenser to the cooling tower, where heat is rejected to the atmosphere. The cooled water then returns to the condenser to absorb more heat from the refrigerant. In the chilled water loop, the evaporator section of the chiller cools the circulating water to a low temperature. This chilled water is pumped to the building's cooling loads such as air handling units and fan coil units where it absorbs heat from indoor air. After absorbing this heat, the now-warmer return water flows back to the evaporator to be re-cooled, completing the cycle. Through continuous circulation and heat exchange, the chiller system provides reliable cooling for buildings and industrial applications.

1.2 Statement of the Problem

Many large institutions rely on a centralised chiller plant to provide cooling across their room and office blocks. This chiller plant operates on a constant chilled water flow rate, regardless of the varying cooling needs of individual office spaces. As a result, the system continues to operate at full capacity even when cooling demands are low, leading to unnecessary energy consumption, increased operational costs, and inefficiencies in the cooling process[13]. The current approach fails to account for the dynamic nature of individual space cooling requirements, which results in wasted energy and higher carbon emissions[14].

In addition, the phenomenon of low delta-T syndrome, where the temperature difference between the supply and return chilled water is reduced below the design level, is common in a centralised chiller plant. This condition often arises during periods of reduced cooling demand and contributes to the inefficiency of the chiller plant, further exacerbating energy waste and increasing costs[1].

There is a need to explore more efficient ways of controlling chilled water flow, particularly through individual space-based flow control. By adjusting the flow of chilled water based on the specific cooling requirements of each office or room, the chiller plant's overall energy consumption can be optimised, leading to potential energy savings and a reduction in the environmental impact of the cooling system[3]. However, the potential benefits of such control strategies, both in terms of energy savings and system efficiency, have not been fully explored or implemented at the University of Nottingham Malaysia.

This research aims to address this gap by investigating the energy performance of the chiller system with individual space chilled water flow control, both through numerical simulations and experimental data. The goal is to identify opportunities for improving system efficiency,

reducing energy consumption, and ultimately providing a sustainable and cost-effective cooling solution for the university[1].

1.3 Aim and objectives of the study

The aim of this research is to investigate the energy-saving potential of implementing individual space chilled water flow control in the chiller system at the University of Nottingham Malaysia through numerical simulations and experimental approach. Specific objectives include;

1. To develop an integrated numerical model of the chilled water system and the case study building that will be used to predict through simulation the temperature and energy behaviour of the case study building based on the constant flow chilled water pump operation
2. To develop a new robust predictive and adaptive chilled water flow control strategy for the operation of the chilled water system based on individual zones demand of the building.
3. To validate the formulated numerical model of the building and chilled water control system through experimental measurement and comparison of actual system performance with simulated performance.
4. To compare the chilled water plant thermal performance based on the conventional constant flow control strategy with the proposed individual space chilled water flow control system

1.4 Contribution and Significance of Research

The findings of this study have the potential to influence energy efficiency practices in educational institutions and other commercial buildings, offering a feasible solution to reduce energy consumption while enhancing operational sustainability.

By exploring individual space chilled water flow control, this research offers deeper insights into how tailoring cooling to the specific needs of each office or room can optimize energy consumption and improve system performance. Additionally, the investigation into low delta-T syndrome, a common issue in chilled water systems, contributes valuable solutions for mitigating its negative impacts. Understanding and addressing this phenomenon is crucial in enhancing the efficiency of chiller systems, which are essential for large-scale cooling operations. The practical applications of this research are especially relevant for the University of Nottingham Malaysia. By focusing on the university's existing chilled water system, this study offers valuable data on the energy-saving potential of adopting individual space chilled water flow control within the institution's infrastructure.

Furthermore, this study contributes to global sustainability efforts. By reducing unnecessary energy consumption in cooling systems, the research supports efforts to mitigate climate change and promote environmentally friendly building operations. The optimization of cooling systems directly aligns with global initiatives for energy conservation and carbon footprint reduction, providing a practical example of how building management can play a pivotal role in achieving these broader environmental goals.

1.5 Scope and Assumptions of the Study

The scope of this study is centred around investigating the potential energy savings and system efficiency improvements that can be achieved through the implementation of individual space

chilled water flow control in the chilled water system at the University of Nottingham Malaysia. Specifically, the research will focus on the chilled water system serving the university's four office blocks. Currently, the system operates with a constant chilled water flow rate, regardless of the varying cooling demands of individual spaces. This study will explore a more dynamic approach, where the flow of chilled water is controlled based on the cooling requirements of each individual office or room.

Additionally, experimental validation will be conducted on-site at the University of Nottingham Malaysia. Data will be collected from the existing chiller system to assess its real-world performance under current operating conditions. The experimental analysis will then test the effectiveness of individual space flow control, providing direct evidence of energy savings and operational improvements to validate the formulated model.

The study will also focus on the development of robust energy savings and operational cost reductions strategy. By comparing the energy consumption patterns before and after implementing individual space flow control, the research will quantify potential savings, providing a detailed assessment of the cost-effectiveness of the proposed solution.

Chapter 2: Literature review

2.1 Introduction

Chilled water systems (CWS) represent one of the most prevalent and efficient heating, ventilation, and air conditioning (HVAC) solutions for providing cooling in large commercial, institutional, and industrial buildings. They are designed to circulate chilled water, produced at a central plant, through an extensive piping network to terminal units such as air handling units (AHUs), fan coil units (FCUs), or variable air volume (VAV) terminals distributed throughout the building. These terminal units facilitate the transfer of heat from the indoor air to the chilled water, effectively lowering ambient temperatures to maintain occupant comfort and meet indoor environmental quality standards[15]. The widespread adoption of chilled water systems is attributed to their scalability, adaptability to varying building sizes, and superior energy performance relative to decentralized or direct expansion cooling systems [16].

In HVAC applications, chilled water systems serve as the backbone of centralised cooling strategies. They are particularly suited to buildings with complex zoning requirements and large, variable cooling loads, such as university campuses, healthcare facilities, airports, hotels, office high-rises, and shopping centres [17]. The basic operation involves the production of chilled water at the central plant using refrigeration cycles, followed by its circulation to multiple terminal units where heat exchange takes place. The warmed water returns to the plant for re-cooling, thus creating a closed-loop system. This approach contrasts with air-cooled or direct expansion systems that cool air or spaces individually, often with lower efficiency and higher maintenance overheads [18].

The modular nature of chilled water systems allows operators to manage energy consumption effectively by controlling chilled water temperatures, flow rates, and distribution according to demand variations, both temporally and spatially within the building. Integration with building management systems (BMS) facilitates real-time monitoring and adaptive control, further optimising energy usage while maintaining indoor comfort[19].

Large-scale commercial and institutional buildings place significant demands on HVAC infrastructure due to their size, occupancy patterns, and diverse functional spaces. Chilled water systems address these challenges by centralising cooling generation and leveraging advanced controls to allocate cooling capacity dynamically. This centralisation promotes economies of scale in equipment sizing, maintenance, and energy management[20].

Moreover, chilled water systems contribute substantially to energy consumption in buildings, accounting for roughly 40–60% of total electricity use in commercial structures, underscoring the imperative for energy-efficient operation [21]. Through demand-based control strategies, variable speed pumping, and integration with renewable energy sources, chilled water systems can substantially reduce carbon footprints and operational costs, aligning with global sustainability goals[16].

Over the decades, technological innovations have driven significant advancements: the introduction of variable primary flow systems, variable frequency drives (VFDs) for pumps and fans, and the deployment of sophisticated digital control algorithms have revolutionised system efficiency and responsiveness.

The modern trend in chilled water systems emphasises intelligent automation and integration. Building management systems now employ data analytics, machine learning, and model predictive control (MPC) techniques to predict cooling loads, optimise sequencing of chillers

and pumps, and detect faults proactively [22]. Furthermore, advancements in sensor technology enable precise monitoring of temperatures, flow rates, pressures, and energy consumption, feeding back into adaptive control loops that fine-tune system operation in real time [23].

Sustainability and energy efficiency remain paramount in recent developments. There is growing adoption of low-global warming potential refrigerants, hybrid cooling solutions combining chilled water with free cooling or geothermal heat exchange, and integration with district energy systems[24]. These trends reflect increasing regulatory pressures and the drive toward net-zero energy buildings worldwide.

At the heart of any chilled water system lies the chiller plant, where the vapour compression refrigeration cycle is utilised. This cycle consists of four essential components: the compressor, evaporator, condenser, and expansion valve. The compressor pressurises refrigerant vapour, increasing its temperature and pressure. The condenser then rejects heat to the environment, condensing the refrigerant to a high-pressure liquid. The expansion valve reduces the pressure and temperature of the refrigerant, allowing it to evaporate in the evaporator where it absorbs heat from the chilled water circuit.

The chilled water loop comprises pumps and piping that deliver cooled water to the building's terminal units. Pumps are critical in maintaining the required flow rate and overcoming hydraulic losses within the distribution system. Proper hydraulic balancing ensures that all zones receive the appropriate flow rates, which is vital to prevent inefficiencies such as “low delta-T syndrome” where the temperature difference between supply and return chilled water decreases, reducing system capacity and increasing energy consumption[25].

Terminal units such as AHUs and FCUs transfer heat from indoor air to the chilled water via heat exchange coils. The chilled water absorbs this heat, warming as it returns to the chiller for

re-cooling. Effective control of chilled water temperature, flow, and terminal unit operation is essential to match cooling supply with demand and optimise energy use[26].

Figure 2.1 illustrates a typical chilled water system schematic showing the central chiller plant, distribution pumps, cooling tower, and terminal units, providing a visual representation of the system's operational components and flow paths.

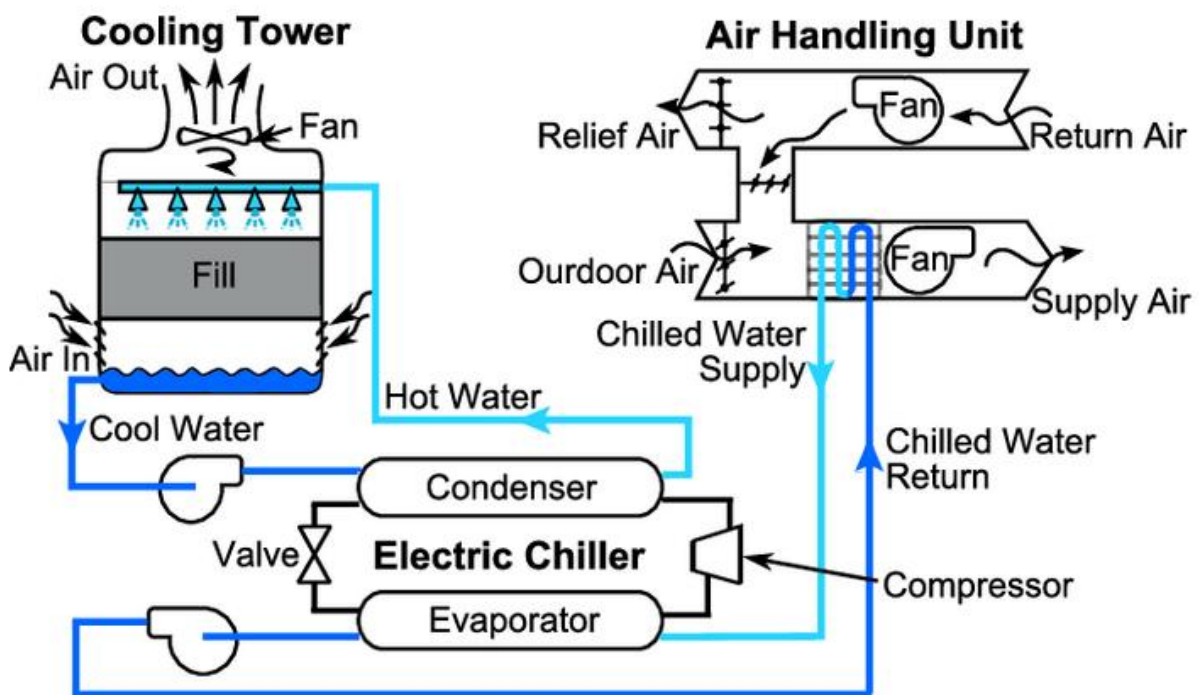


Figure 2.1, Schematic of typical Chilled Water System (CWS). [27]

The design and operation of chilled water systems have become increasingly important due to the high energy consumption associated with HVAC systems, which can account for up to 50% of total building energy use [28]. Therefore, optimising chilled water systems is essential for reducing operational costs and minimising environmental impacts [29].

Recent technological advancements have enhanced the energy efficiency of chilled water systems by incorporating variable flow control, advanced pumping systems, and integration with building automation systems [30]. These technologies allow dynamic modulation of chilled water flow to match varying zone cooling demands, resulting in improved energy savings and occupant comfort [31].

In conclusion, chilled water systems are pivotal to modern HVAC strategies in large buildings. A comprehensive understanding of their components, operation, and recent innovations is critical for further research focused on energy-saving control strategies.

Cooling occurs by directing heated air into the air handling unit, where it passes over the coil, facilitating the transfer of cooling to the air being expelled, thus cooling the room or process. Simultaneously, the warm air traverses the coil, transferring heat to the water, which exits the air handling unit at an elevated temperature. Warm water circulates back into the piping and risers, which return to the chiller's evaporator for re-chilling. The chiller generates heat during the refrigeration cycle that cools the evaporator water. The chiller extracts heat on the condenser side, leading to the expulsion of warm water.

Warm water is conveyed to a cooling tower, often situated on the building's roof, via risers and piping. A cooling tower gathers heated condenser water and disperses it within the tower, enabling it to descend and be collected at the base. In the cooling tower, substantial fans are employed to intake ambient air from outside the building and mix it with the heated condenser water for cooling purposes. Warm air is produced from the condenser water and subsequently expelled from the cooling tower into the external atmosphere. The cooled water at the base of the cooling tower is gathered and redirected to the condenser, where it circulates over coils to facilitate heat transfer from the chiller, perpetuating the cycle. A chilled water system consists

of two closed piping loops; no water circulates between the evaporator and condenser loops, only the refrigerant.

2.2 Global Energy Consumption

Heating, ventilation, and air conditioning (HVAC) systems account for a significant portion of energy consumption in buildings globally, representing approximately 30–40% of total building energy use [32]. In developed countries, this share can rise to 50% of building energy consumption and approximately 20% of national energy use [33]. Within the residential sector, HVAC systems contribute to about one-third of global energy consumption, corresponding to roughly 8% of total final energy use [34].

The demand for HVAC energy is expected to increase substantially due to factors such as population growth, rapid urbanization, rising expectations for thermal comfort, and the effects of climate change, particularly in emerging economies. [34] A major driver of this demand is the widespread adoption of air conditioning, with the proportion of households equipped with Air Conditioner (AC) projected to increase from 27% in 2020 to 41% by 2050. This trend is expected to nearly double global residential cooling electricity consumption, from 1,220 TWh to 1,940 TWh per year [35].

In specific national contexts, HVAC energy use is also significant. For instance, in the United States, HVAC systems consume approximately 35% of total primary energy, and China is anticipated to reach similar levels in the near future [35]. Moreover, energy demand for space cooling is increasing at an estimated rate of 5% per year in certain regions, driven by both climate change and economic development [35]. Table 2.1 is the summary of the regional energy consumption share of HVAC systems in building.

Table 2.1: Global and regional energy consumption share of HVAC systems in buildings

Region/Sector	HVAC Share of Energy Use	Notable Trends	Citations
Global Buildings	40–60%	Largest end-use in buildings	[36]
U.S. Buildings	50%	20% of total national energy use	[36]
Residential (Global)	32%	8% of total final energy use	[34]
U.S. Primary Energy	35%	China approaching similar share	[37]
Air Conditioning (Global)	From 27% to 41% (2020–2050)	Doubling of global cooling demand	[8]

Overall, HVAC systems are responsible for a significant and growing share of global energy consumption, especially in buildings. With rising demand for cooling and increased focus on indoor air quality, energy use is expected to continue increasing unless efficiency measures and advanced controls are widely adopted.

2.3 Overview of Chilled Water Systems

2.3.1 General Description

Chilled water systems (CWS) are highly efficient cooling mechanisms extensively used in Heating, Ventilation, and Air Conditioning (HVAC) applications, particularly for large commercial buildings. Their operation, role in HVAC, and significance in meeting the cooling requirements of commercial spaces [38].

A typical chilled water system comprises several integral components that collectively ensure effective cooling delivery. Chillers serve as the primary units, employing mechanical refrigeration to lower water temperature to approximately 4.5–7.2°C, which is subsequently circulated throughout the building [39]. The piping network, consisting of insulated supply lines (delivering chilled water from the chiller to terminal units) and return lines (returning warmed water to the chiller), facilitates efficient fluid distribution. Air Handling Units (AHUs) and Fan Coil Units (FCUs) act as terminal devices, transferring thermal energy from the chilled water to the air via heat exchangers and delivering conditioned air to indoor spaces. Supporting ancillary components, including pumps, valves, expansion tanks, and control systems, ensure reliable operation and effective management of the chilled water loop.

Chilled water systems operate on fundamental thermodynamic principles. Water is cooled centrally within the chiller, typically using energy-intensive refrigerants, although alternative technologies such as adsorption refrigeration are increasingly applied in modern systems. The chilled water is then conveyed through the distribution network to terminal units (AHUs or FCUs), where it absorbs heat from indoor air, raising the water temperature before it is returned to the chiller for re-cooling. Systems may also incorporate cooling towers for heat rejection via evaporative cooling, thereby improving overall energy efficiency.

Water is widely adopted as the primary cooling medium due to its high specific heat capacity, efficient thermal energy transfer characteristics, and ability to maintain consistent temperature control across the building's distribution network.

Chilled water systems play a pivotal role in modern HVAC configurations due to their multiple operational advantages. They provide both cooling and dehumidification by circulating air over chilled water coils, effectively removing heat and moisture from indoor spaces, which ensures occupant thermal comfort. This dual functionality renders chilled water systems particularly suitable for humid climates. In terms of energy efficiency, these systems outperform decentralized cooling solutions, such as individual air conditioners, by centralizing the generation of chilled water and distributing it through insulated pipelines using pumps. This approach reduces energy losses associated with less efficient refrigerant-based loops. Furthermore, chilled water systems exhibit remarkable scalability and adaptability, accommodating a wide spectrum of cooling demands, from small office buildings to large-scale facilities such as hospitals and data centers. Their operational flexibility, including variable flow rates and adjustable temperature setpoints, allows dynamic adaptation to fluctuating load requirements. Zonal flexibility is another key advantage, as modern installations equipped with variable speed drives (VSDs) and advanced control algorithms can deliver precise cooling to individual zones, simultaneously enhancing energy performance and occupant comfort. Additionally, chilled water systems can be integrated with renewable energy sources, such as solar photovoltaic systems, to create sustainable HVAC solutions. Such integration not only reduces operational energy costs but also contributes to lower carbon emissions, supporting compliance with stringent building efficiency standards.

2.3.2 Importance in Large Commercial Buildings

Large commercial buildings, including shopping malls, office complexes, hospitals, and data centres, extensively rely on chilled water systems due to their operational flexibility, energy efficiency, and capacity to maintain high-quality indoor environmental conditions at scale. These systems are particularly effective in managing high cooling loads, which arise from elevated occupant density, substantial electronic equipment usage, and large glazed surfaces that contribute to increased internal heat gains. Chilled water systems can efficiently meet these demands, even during peak operating hours.

In terms of energy cost reduction, modern chilled water systems equipped with predictive modelling and advanced control strategies, such as Model Predictive Control (MPC) and online optimization, are capable of delivering cooling precisely where and when it is needed, thereby minimizing energy waste [40]. Furthermore, chilled water systems support sustainability goals, as HVAC systems in commercial buildings account for approximately 35% of global electricity consumption, with cooling representing a significant portion [40,41]. The application of energy optimization techniques including variable-speed pumps and particle swarm optimization ensures minimal energy consumption while maintaining thermal comfort. Integration with renewable technologies, such as solar-driven chillers, can further reduce annual operating emissions, contributing to broader environmental objectives [42].

Chilled water systems also enable precise indoor environmental regulation, allowing the creation of customized thermal zones that enhance occupant comfort, productivity, and well-being. Their reliability and maintainability stem from their robust, centralized design, which facilitates easier monitoring and maintenance compared to decentralized cooling methods. Predictive maintenance strategies can further reduce system downtime and optimize performance, particularly in mission-critical settings such as hospitals and data centres [43].

Lastly, the modular and centralized architecture of well-designed chilled water systems ensures longer operational lifespans, with the flexibility to implement upgrades and expansions without significant disruption to building operations.

2.3.3 Energy Consumption and Performance Characteristics of CWS

Chilled water systems (CWS) contribute substantially to the overall energy consumption in large commercial and institutional buildings, typically accounting for 30–50% of the HVAC energy load [44]. The energy usage varies throughout the day and year, driven by factors such as building occupancy, internal heat gains, and ambient weather conditions. Peak cooling demand during hot periods leads to higher electricity consumption, while low-load periods often result in inefficiencies when systems operate without adjustment [45]. Dynamic cooling load profiles across multiple zones within a building create challenges in matching chilled water delivery with actual demand, which if not properly managed, leads to unnecessary energy consumption.

The main contributors to energy use in chilled water systems are chillers, pumps, and cooling towers. Chiller efficiency is strongly affected by part-load operation, the temperature difference between the chilled-water supply and return (commonly referred to as delta-T), and the surrounding ambient conditions [19]. Delta-T represents how much the temperature of the chilled water rises as it passes through the cooling loads. A higher delta-T indicates that the chilled water is absorbing heat effectively, meaning the cooling coils are operating as intended and the system requires a lower water flow rate to achieve the desired cooling effect. In contrast, a low delta-T occurs when the temperature rise across the cooling load is insufficient. Pumps consume energy depending on flow rates and system pressure losses; hydraulic imbalances or oversized equipment increase power usage significantly [46]. Cooling towers also contribute to energy use via fans and water treatment processes, where inefficiencies can

escalate operational costs [47]. Furthermore, control strategies such as fixed setpoints and constant flow pumping reduce opportunities to save energy under variable load conditions [48].

Conventional chilled water plants mainly use constant flow pumping and fixed temperature setpoints, which often lead to energy wastage, especially during partial load periods [49]. These systems fail to adjust chilled water flow to match real-time demand, resulting in over-pumping, frequent chiller cycling, and associated wear and inefficiencies. A significant issue is the low delta-T syndrome, where the temperature difference between supply and return chilled water decreases below design levels, causing increased water flow and suboptimal chiller operation [50]. These inefficiencies highlight the necessity for more advanced control methods and hydraulic optimisation.

Low delta-T syndrome forces chilled water systems to pump excessive volumes of water, reducing thermal efficiency and increasing both electrical consumption and operational costs [51]. It also results in more frequent equipment maintenance and higher carbon emissions. Implementing demand-responsive flow control, optimised hydraulic balancing, and adaptive temperature setpoint control can substantially mitigate these issues, leading to significant energy savings and improved system reliability [52].

2.3.4 Chilled Water Systems Energy Efficiency

Water chilling systems exhibit considerable energy efficiency, as the chiller the primary electricity consumer activates solely when the reservoir temperature attains a predetermined threshold [1]. Nonetheless, the energy utilised for cooling constitutes a significant portion of the overall energy consumption and utility expenses of a structure [5]. Consequently, any optimisations or efficiencies that may be implemented to achieve energy savings are highly appreciated, particularly for high-demand customers [13]. Another concern regarding the

energy efficiency of water-cooled chiller systems is the emissions generated as a by-product of energy usage. Climate change constitutes a significant hazard, and diminishing energy use directly correlates with a decrease in greenhouse gases, especially carbon dioxide (CO₂) emissions [3].

2.3.5 Performance Evaluation in Chilled Water System

Chilled water systems (CWS) are indispensable for centralised cooling applications in large commercial and institutional buildings [53]. These systems provide thermal comfort by circulating chilled water through a network of pipes connected to air handling units (AHUs), fan coil units (FCUs), or terminal units [54]. Performance evaluation of a chilled water system is crucial for optimising energy use, maintaining indoor thermal comfort, and ensuring long-term operational reliability [55].

Evaluating system performance involves analysing multiple parameters including thermodynamic efficiency, hydraulic stability, energy consumption, and control responsiveness [56]. The integration of performance evaluation frameworks enables building operators and engineers to identify operational inefficiencies, apply corrective measures, and benchmark performance against industry standards [57].

Key performance indicators (KPIs) include the Coefficient of Performance (COP), which measures the ratio of useful cooling energy output to electrical energy input of the chiller [58]. A higher COP value indicates superior energy performance. Another critical indicator is the chilled water temperature differential, or Delta-T defined as the difference between the supply and return chilled water temperatures. A low Delta-T, often symptomatic of coil overfeeding or underloading, can result in inefficient operation and excessive pump energy use [59]. Energy Use Intensity (EUI), measured in kWh/m²/year, offers a normalised comparison of

energy performance across different buildings and usage profiles [60]. Specific Energy Consumption (SEC), expressed in kWh/ton-hour of cooling, quantifies the energy efficiency of the overall system and is useful in cost analysis and lifecycle assessment [61]. The system-wide COP (SCOP) accounts for energy consumed by chillers as well as pumps and cooling towers, providing a comprehensive measure of plant efficiency [62].

Thermal and hydraulic performance assessments are central to understanding a chilled water system's ability to meet cooling loads efficiently while minimising energy consumption [63]. Thermal performance involves evaluating the system's responsiveness to dynamic cooling loads and capacity to maintain target indoor temperatures. Inefficiencies may arise from improper control sequences, oversized chillers, or poor insulation [53]. Hydraulic performance is evaluated by assessing pressure and flow behaviour within the distribution network. Efficient hydraulic systems deliver appropriate flow rates at minimal pump energy [54].

Variable Primary Flow (VPF) configurations modulate flow through chillers in response to load demands, eliminating the need for secondary pumping loops and reducing energy losses from over-pumping [56]. Variable frequency drives (VFDs) on pumps allow dynamic flow adjustment; small reductions in pump speed led to disproportionately large energy reductions according to the Affinity Laws [58].

Effective load matching and control strategies enhance the energy efficiency and responsiveness of chilled water systems. Traditional fixed setpoint control methods often cause inefficiencies under varying loads. Adaptive setpoint control continuously adjusts chilled water supply temperature (CHWST) based on real-time loads and environmental conditions, improving efficiency and reducing chiller energy use [55].

Fault Detection and Diagnostics (FDD) techniques use sensor data to identify operational deviations early, enabling proactive maintenance and preventing energy losses [59]. Automated FDD systems can reduce building energy consumption by up to 30% through early anomaly detection and corrective interventions [63]. Continuous commissioning, routine performance monitoring, and recalibration further enhance long-term energy performance.

2.4 Chilled Water Systems and Green Building Sustainability

Chilled water systems play a pivotal role in achieving sustainability objectives in green building design, as highlighted by prominent standards such as Leadership in Energy and Environmental Design (LEED), Green Real Estate (GreenRE), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) guidelines. These frameworks establish performance benchmarks and promote optimization strategies that enhance energy efficiency while contributing to broader climate mitigation targets [64].

In the context of green building certification, LEED recognizes projects that optimize energy performance through measures such as upgrades to chilled water systems, implementation of efficient control strategies, and integration with renewable energy sources. Empirical evidence indicates that LEED-certified projects can achieve energy savings of approximately 16–30% following retrofits, with optimization of chilled water plants being a significant contributor to such savings [65].

Similarly, ASHRAE standards, particularly ASHRAE Standard 90.1 and the ASHRAE Green Guide, advocate for designs that maintain high temperature differentials (ΔT) ranging from 7–10 Kelvin and employ variable-speed drives for pumps and fans. These strategies can produce energy savings of 12–28% in chilled water systems [64].

2.5 Chilled Water System Modelling and validation

Numerical modelling and simulation have become indispensable tools for analysing and optimising chilled water systems in HVAC applications. These techniques enable researchers and engineers to replicate complex thermal and hydraulic behaviours of chilled water plants under varying operating conditions. Through simulation, it is possible to evaluate the impacts of different system configurations, control strategies, and load scenarios on energy consumption and occupant comfort. Moreover, integrated modelling that couples building thermal dynamics with chilled water system hydraulics facilitates comprehensive performance assessments, guiding effective energy-saving interventions and operational improvements. This section explores the role, methods, applications, and challenges of numerical modelling in chilled water systems.

Numerical models allow the simulation of chilled water plant operation in a cost-effective and controlled environment, which is invaluable for design optimisation, control strategy development, and energy performance evaluation [66]. By modelling the interactions among chillers, pumps, cooling towers, and building loads, numerical simulations provide insights into system efficiencies and potential areas for energy savings. Such models support decision-making processes, enabling stakeholders to predict outcomes of operational changes before real-world implementation [67]. Additionally, these models are crucial in developing advanced control algorithms that enhance plant responsiveness and reduce energy use.

Various modelling approaches are applied depending on the study objectives and complexity of the system. Steady-state models focus on snapshot analyses, ideal for equipment sizing and peak load estimation [68]. Dynamic models simulate transient behaviours, incorporating time-dependent load changes, control responses, and environmental variations for detailed operational assessment [69]. Hydraulic network modelling solves fluid flow and pressure

equations to evaluate pump energy and flow distribution, while thermal models predict temperature variations in the chilled water loop and heat transfer within terminal units.

TRNSYS is a modular transient systems simulation program designed to model complex energy systems by breaking them down into smaller components known as “Types” [87]. These components range from simple devices like pumps to complex multi-zone building models. TRNSYS Simulation Studio provides an integrated visual interface for configuring and connecting components. Users input building data and define system components and their connections, resulting in a set of difference and algebraic equations solved by the simulation engine [88].

The TRNSYS library includes components for low-energy buildings, HVAC systems, renewable energy, cogeneration, fuel cells, solar thermal, and photovoltaic systems, along with a comprehensive multizone building model. Its modular architecture facilitates adding new mathematical models and integrating components developed in other programming languages, such as Matlab/Simulink, Excel/VBA, and EES [89].

Written in Fortran, TRNSYS contains components commonly found in energy systems, weather data processing routines, and facilities for simulation result generation. It has become a standard reference worldwide for evaluating systems with time-varying behaviours, including fuel cells, cogeneration, HVAC systems, renewable energy systems, low-energy buildings, and solar systems [90]. TRNSYS’s “Type 56” building model complies with ANSI/ASHRAE Standard 140-2001 requirements and the European Directive on the Energy Performance of Buildings[91]. Over the past two decades, TRNSYS has been extensively used for building energy system simulations, with systematic studies comparing its performance against experimental results and other industry standards [92–95].

It is challenging to measure and enhance system performance consistently due to the lack of standardised benchmarks and best practices for chilled water flow control across different climates and building types [62]. Setting precise standards could direct the sector towards designs that are more efficient [58]. The detail level of Type 56 and the application of Building Energy Simulation in sizing and design comply with the technical standards set by the European Directive on the Energy Performance of Buildings. Over the past two decades, TRNSYS has been extensively utilised in simulations of building energy systems. Systematic studies exist that compare the performance of this program with experimental results, as well as juxtaposing TRNSYS results with other industry standards for building energy simulation.

Experimental validation is a critical component in the development and application of numerical models for chilled water systems. Due to the inherent complexity of chilled water plants encompassing thermal loads, hydraulic networks, control systems, and varying operational conditions purely theoretical models cannot reliably predict system performance without empirical corroboration.

While TRNSYS is particularly suited for transient, component-based simulations of energy systems, other numerical modeling and simulation tools are also commonly employed depending on the objectives of the study. A variety of specialized tools Modelica/Dymola, EnergyPlus, TRNSYS, MATLAB/Simulink, OpenModelica, and ANSYS Fluent are commonly used for numerical modeling and simulation of chilled water systems, each supporting different aspects of system analysis, control, and optimization. Numerical modeling and simulation of chilled water systems use a range of specialized software tools, mathematical models, and optimization algorithms to analyze, predict, and optimize system performance.

Modelica is widely used for dynamic, equation-based modeling of chilled water systems, including system-level and equipment-level control evaluations. Modelica libraries allow for detailed simulation of system configurations and control strategies [70]. EnergyPlus is another tool that is a flexible, high-accuracy energy simulation program used to model chilled water systems and optimize operational parameters, often combined with optimization algorithms for energy efficiency studies [71]. MATLAB/Simulink are both frequently used for developing and testing control algorithms, state-space models, and optimization routines for chilled water systems [71]. Table 2.2 compares the simulation tools for chilled water system and their main area of application.

Table 2.2: Simulation tools and their applications in chilled water system modeling

Tool / Platform	Main Application Area	Citations
Modelica/Dymola	Dynamic system modelling, control evaluation	[70]
EnergyPlus	Energy simulation, optimization	[71]
TRNSYS	Thermal modelling, transient simulation	[72]
MATLAB / Simulink	Control, optimization, state-space modelling	[71]
ANSYS Fluent (CFD)	Fluid dynamics, heat transfer analysis	[73]

Validation against measured field data confirms the accuracy of these models, identifies their limitations, and enables refinement for improved predictive capability. A landmark study by Chen et al. demonstrated the effectiveness of this approach through the implementation of Model Predictive Control (MPC) in a commercial chilled water plant [74]. The researchers gathered extensive operational data, including flow rates, supply and return water temperatures,

power consumption, and ambient conditions. The measured energy savings of approximately 25% closely matched the simulation forecasts, confirming the model's validity [74]. This study also underscored the importance of capturing transient operational phenomena such as load fluctuations, sensor noise, and time delays inherent in control systems factors that are often idealised or neglected in purely numerical simulations. By integrating real-world variability, the validation process improved the robustness and applicability of the control algorithm.

Yoon et al. further substantiated the role of experimental validation by comparing numerical simulation outputs with detailed measurements from a multi-zone commercial building employing a variable flow chilled water system [75]. The strong correlation between observed and simulated temperatures, flow rates, and energy consumption validated the hydraulic and thermal models. This congruence not only enhanced confidence in model-based optimisation of flow control but also provided critical insights into system behaviour under dynamic occupancy and environmental conditions. Their work highlights how experimental data enable precise calibration of model parameters, including valve characteristics, pump curves, and heat exchanger performance [75].

Validation also reveals operational challenges that numerical models may not fully encapsulate. For instance, equipment degradation over time such as pump wear, fouling in coils, and valve leakage affects system efficiency and can introduce discrepancies between predicted and actual performance. These aging factors are difficult to model explicitly but can be inferred and accounted for through long-term experimental monitoring. Similarly, nonlinearities in component behaviour, such as non-ideal pump affinity laws at partial loads or valve hysteresis, become apparent during field validation and guide necessary model adjustments.

A critical aspect of successful validation is the iterative calibration of numerical models. Initial simulations are typically based on manufacturer specifications and design parameters, but discrepancies identified through measurement comparisons necessitate parameter tuning. This process improves the accuracy of models, particularly in reflecting site-specific characteristics such as piping layouts, insulation quality, and control system settings. Calibration is essential when adapting models for retrofit projects or diverse building types where original design data may be incomplete or outdated.

The temporal and spatial resolution of experimental data significantly influences validation quality. High-frequency measurements can capture rapid transient events, such as sudden changes in occupancy or weather, which impact chilled water load demands and control responses. Similarly, spatially distributed sensors allow for analysis of temperature gradients and flow distribution within multi-zone systems, providing a detailed basis for validating zone-level control strategies.

Advanced experimental setups often incorporate comprehensive data acquisition systems capable of integrating measurements from temperature sensors, flow meters, pressure transducers, and electrical power monitors. These systems facilitate continuous monitoring, enabling performance assessment over extended periods and under varying seasonal conditions. Long-term data collection supports the evaluation of system reliability, maintenance needs, and degradation trends, aspects critical to lifecycle energy analysis but challenging to simulate.

Uncertainty quantification is another key element emerging from experimental validation efforts. Measurement errors, sensor calibration drift, and external disturbances contribute to uncertainties in both experimental data and model outputs. Quantifying these uncertainties

allows researchers to assess confidence intervals for simulation predictions and to develop control algorithms robust to such variability.

Moreover, successful validation provides a foundation for deploying predictive and adaptive control strategies with confidence. Field-validated models ensure that control actions, optimized in simulation, translate effectively into energy savings and comfort improvements in real buildings. Consequently, experimental validation acts as a linchpin in advancing the practical implementation of innovative chilled water control technologies.

5.4 Experimental Investigations on Individual Space Flow Control

Yang et al. explore the effectiveness of spray evaporative cooling in enhancing the performance of air-cooled chiller condensers [76]. Through a series of controlled experiments, the study measures the impact of different spray rates and airflow configurations on heat dissipation efficiency. The results demonstrate that spray evaporative cooling improves the heat transfer rate, increasing overall condenser efficiency by up to 15% under high-temperature conditions. While the findings are robust, the study focuses solely on air-cooled condensers and does not extend to other chiller configurations, limiting its broader application. The paper provides valuable experimental data on improving chiller performance, but further work is needed to understand its impact on full system performance [76].

Catrini et al. present a study on advanced control strategies for air-cooled chillers, with a focus on energy savings and system optimization in space cooling applications [77]. The authors use advanced modelling techniques to simulate the performance of air-cooled chillers under varying operational conditions. The results indicate that adaptive control strategies reduce energy consumption by 10-20% while maintaining effective cooling. While the paper's modelling provides significant insights into energy efficiency, it does not delve into the specific

mechanisms of space flow control, such as airflow management, limiting its practical applicability for real-world systems. The study offers a strong foundation for future research on energy-saving control strategies but requires additional experimental validation [77].

Sarbu et al. conduct an advanced modelling study to evaluate control strategies for air-cooled chillers used in space cooling applications [78]. The study simulates various operational conditions, including temperature regulation and airflow management, to optimize chiller performance. The results show that optimized control strategies, particularly those focusing on dynamic regulation of airflow and temperature, can significantly improve energy efficiency and cooling output during periods of high cooling demand. However, the study relies entirely on simulation-based results, which limits its immediate application to real-world systems. The findings offer valuable insights for future space flow control strategies but require experimental validation to confirm the model's predictions in practical settings [78].

Individual space chilled water flow control has been a focus of recent experimental research due to its potential to deliver substantial energy savings and enhanced occupant comfort. Morejón et al. implemented electronically actuated flow control valves in a university building, monitoring the system's energy performance over several months [79]. They observed a 15% reduction in chiller electricity consumption and improved temperature stability in individual zones compared to traditional centralised control [79].

Fu et al. equipped an office tower with smart thermostats and modulating flow valves for individual zones [80]. Experimental results demonstrated reductions in pumping energy and chilled water consumption, alongside occupant-reported comfort improvements. The study also documented challenges in integrating control hardware with legacy systems and managing sensor calibration, providing valuable lessons for practical implementations [80].

Henclewood et al. highlighted that iterative calibration using experimental data significantly enhances model accuracy, allowing simulations to better capture nonlinearities and dynamic behaviour[81]. Such calibrated models become invaluable tools for testing control strategies and predicting system responses to new operating conditions. Continuous feedback loops between modelling and experimentation foster progressive improvements in chilled water system design and management [81].

2.6 Chilled Water Flow Control Strategies

Chilled water flow control is a critical component in the efficient operation of centralized cooling systems, directly influencing energy consumption, thermal comfort, and system reliability. The primary objective of flow control is to deliver the required cooling capacity to individual zones or terminal units while minimizing energy losses in pumps, chillers, and distribution networks. There are different flow control strategies viz:

Traditional Constant Flow Chilled Water Systems: Traditional chilled water systems typically employ constant flow pumping, where chilled water circulates at a fixed volumetric flow rate regardless of the varying cooling demands within the building [50]. This approach simplifies hydraulic design and control but leads to significant inefficiencies. Because chilled water is continuously pumped at the design flow rate, energy is wasted during partial load periods when many zones require less cooling. Additionally, constant flow systems struggle to maintain adequate temperature differentials (ΔT), which compromises chiller efficiency and increases energy consumption [51].

The fixed nature of constant flow systems results in unnecessary pump energy use and frequent chiller cycling, accelerating wear and increasing maintenance costs. Moreover, the lack of

responsiveness to dynamic cooling loads can cause occupant discomfort due to uneven temperature distribution and delayed system reaction times [51].

Variable Flow Systems: Variable flow chilled water systems, notably Variable Primary Flow (VPF) configurations, adjust the chilled water flow rate based on real-time cooling demand. This modulation is typically achieved using variable speed pumps controlled by differential pressure sensors or zone temperature feedback [82]. By reducing flow during low load conditions, VPF systems significantly cut pumping energy consumption and enhance chiller performance by maintaining higher delta-T values [19].

VPF systems also reduce mechanical stress on equipment and improve occupant comfort by providing more stable temperature control. Recent studies indicate that variable flow strategies can reduce chilled water plant energy use by 10% to 30% compared to constant flow systems, highlighting their importance in sustainable building design [83–85].

Individual Space Chilled Water Flow Control: Individual space chilled water flow control takes granularity a step further by regulating chilled water delivery at the zone or terminal unit level rather than at the plant or floor level. This approach ensures that each room or space receives precisely the amount of chilled water required to meet its unique cooling demand, enhancing system efficiency and occupant comfort [86].

Technologies enabling individual flow control include electronically actuated valves, intelligent thermostats, and smart sensors that monitor space temperatures and humidity[87]. Coupled with advanced control algorithms, these technologies enable real-time adjustments to flow rates, avoiding overcooling and unnecessary energy consumption in unoccupied or lightly loaded zones [88].

Demand-Driven Flow Control : Demand-driven flow control, whereby chilled water delivery matches the actual cooling load in real time, is critical for maximising energy efficiency and operational performance [89]. By avoiding unnecessary flow and maintaining optimal Delta-T values, demand-driven strategies reduce pump energy, lower chiller runtime, and minimise cycling losses [90].

Furthermore, demand-driven control enables finer thermal zoning, which improves occupant comfort and reduces peak loads on the plant. The integration of demand-driven flow control with building management systems facilitates continuous monitoring, fault detection, and automated optimisation, driving towards sustainable and cost-effective chilled water plant operation [91]. Table 2.3 is the comparison of the conventional and variable speed flow control of the chilled water energy system.

Feature	Traditional (Constant Flow) System	Variable Flow System	References
Pump Operation	Constant speed pumps; fixed flow	Variable speed pumps: flow adjusts to load	[19]
Control Method	On/off control or constant setpoint control using basic Proportional–Integral–Derivative (PID) controllers	advanced control methods such as enhanced Proportional–Integral–Derivative (PID), Fuzzy Logic Control, Artificial Neural Networks (ANN), Model Predictive Control (MPC), and adaptive setpoint reset strategies	[92]
Energy Efficiency	Lower; pumps run at full capacity regardless of load	Higher; significant energy savings (10–58%) possible	[19]
System Complexity	Simple design and control	More complex; requires sensors and advanced control	[92]

2.7 Building integration with chilled water systems

Accurate and reliable simulation of building energy performance requires an integrated modelling approach that couples chilled water system models with comprehensive building thermal models. This integration is vital for capturing the complex interactions between the building envelope, internal heat gains, HVAC equipment, and control strategies, which isolated or standalone models cannot fully represent.

Building thermal models simulate the dynamic heat flows within a structure, accounting for factors such as heat gains from occupants, electrical equipment, lighting, and solar radiation through windows and walls. These internal loads vary temporally based on occupancy schedules, equipment usage patterns, and weather conditions, creating a spatially and temporally heterogeneous cooling demand throughout the building [93]. When coupled with chilled water system models which represent the hydraulic and thermal behaviours of chillers, pumps, valves, and distribution networks this integration allows for precise prediction of the cooling load supplied by the chilled water plant and the system's response to real-time demand fluctuations.

This coupled simulation approach offers multiple advantages. First, it enables realistic and dynamic calculation of chilled water flow rates, supply and return temperatures, and energy consumption across different parts of the building. Such detail is essential for understanding system-level performance metrics like chilled water temperature differential (ΔT), pumping energy, and chiller efficiency. Second, integrated models facilitate the assessment of advanced control strategies (e.g., variable flow control, model predictive control) in the context of actual building operating conditions rather than idealised scenarios. This contextual evaluation helps identify control system interactions with occupant behaviour and environmental variations that can affect performance and comfort.

From a methodological perspective, the integration of building thermal models and chilled water system models is commonly achieved through co-simulation frameworks. Platforms such as EnergyPlus a widely used, open-source building energy simulation program are frequently coupled with dynamic system modelling environments like Modelica or TRNSYS. EnergyPlus accurately predicts internal heat gains, zone temperatures, and ventilation rates, while Modelica and TRNSYS provide detailed physical and control models of chilled water plant components and networks [48]. Communication between these platforms occurs at defined time steps, enabling the exchange of boundary conditions such as zone cooling loads and chilled water supply temperatures.

Challenges in building-integrated chilled water system simulation include ensuring data consistency, managing computational complexity, and accurately modelling the bidirectional interactions between the building and its HVAC plant. For instance, changes in chilled water supply temperature influence indoor conditions such as temperature and relative humidity, which in turn affect internal loads, creating a feedback loop that must be captured with high fidelity. Additionally, the large scale and complexity of multi-zone buildings require sophisticated zoning and parameterisation strategies to maintain manageable simulation run times without sacrificing accuracy.

The development of integrated digital twins for buildings and HVAC plants is a growing trend, providing near-real-time simulation and optimisation capabilities. These digital replicas allow facility managers to monitor system performance continuously, detect faults early, and evaluate energy-saving interventions virtually before implementation, significantly enhancing operational efficiency and sustainability.

2.8 Review of past work on chilled Water System

2.8.1 Simulation Studies on Chilled Water System

Numerical simulation has become an indispensable tool in the optimisation and analysis of chilled water systems due to its ability to model complex thermal, hydraulic, and control interactions under varying operational scenarios. A wide range of studies have demonstrated how simulation techniques can be employed to enhance energy efficiency, improve system reliability, and support advanced control strategies.

One of the most significant applications of numerical simulation is in evaluating the impact of advanced control methodologies such as Model Predictive Control (MPC). Ra et al. presented a comprehensive study where MPC was utilised to dynamically optimise chilled water flow rates and supply temperatures in a commercial building [94]. By forecasting cooling loads using real-time data and predictive algorithms, MPC effectively adjusted plant operation to minimise energy consumption without compromising occupant comfort. Their findings revealed energy savings of up to 25% compared to conventional rule-based controls, showcasing the potential of predictive control integrated with simulation for substantial efficiency gains [94].

Beyond control optimisation, simulation studies have extensively explored hydraulic design optimisation. Zhang et al. emphasised the critical importance of accurate modelling of flow paths, pipe sizing, and pump characteristics within the chilled water distribution network [95]. By optimising these hydraulic parameters, simulation studies have demonstrated significant reductions in pump energy consumption, which often constitutes a large fraction of total system energy use. Properly calibrated hydraulic models allow for the identification of bottlenecks, pressure drops, and inefficient flow patterns, thereby guiding design modifications and operational adjustments that enhance system efficiency and reliability.

Another important application area of simulation is the analysis of low delta-T syndrome, a phenomenon where the temperature difference between supply and return chilled water is significantly below design levels. Dai et al. utilised dynamic simulation to investigate the causes and consequences of low delta-T syndrome under different load conditions and control strategies [96]. Their work highlighted how simulation can be employed to test corrective measures such as variable flow pumping, enhanced control sequences, and hydraulic balancing, providing insights that are difficult to obtain through field measurements alone.

Despite these successes, several challenges remain in the effective simulation of chilled water systems. One key difficulty lies in capturing the nonlinear behaviour of equipment such as chillers, pumps, and valves, whose performance varies considerably with operating conditions. Accurate representation of nonlinearities requires detailed manufacturer data and sophisticated component models, which are not always readily available or easy to integrate [97].

Furthermore, hydraulic interactions within complex piping networks introduce additional complexity. Pressure losses, flow recirculation, and transient hydraulic phenomena must be accurately modelled to predict system behaviour under variable demand accurately. These interactions become particularly challenging to simulate in large buildings with extensive chilled water distribution systems serving multiple zones with diverse load profiles.

Real-time control dynamics add yet another layer of complexity. Control algorithms often involve discrete decisions, feedback loops, and time delays, which require integration of simulation platforms capable of co-simulating physical processes and control logic. Ensuring numerical stability and computational efficiency during such co-simulations, especially for large-scale systems, remains an active area of research.

The computational demand of dynamic simulations can be substantial, often necessitating trade-offs between model fidelity and simulation run time. Simulations that incorporate detailed zone-level thermal models, extensive piping networks, and transient control behaviours may require high-performance computing resources or long execution times, potentially limiting their practical applicability for iterative design or real-time optimisation.

Furthermore, the incorporation of occupant behaviour and weather variability is essential to achieve realistic performance predictions. Occupant presence, activities, and control interactions can cause significant fluctuations in cooling loads, while weather variations influence building envelope heat gains and cooling plant operation. Nguyen et al. highlighted the importance of stochastic or scenario-based modelling approaches to capture this variability, although doing so further increases model complexity and computational requirements [48].

2.8.2 Chilled Water Control Methods

Modern chilled water systems increasingly adopt advanced control strategies that incorporate prediction and adaptation to optimize performance. Predictive control methods use historical data and building models to forecast future cooling loads and adjust chilled water flow accordingly [98]. Adaptive control algorithms continuously refine control parameters based on real-time system feedback, improving responsiveness to unforeseen changes [99].

Model Predictive Control (MPC) has gained prominence for its ability to optimise multiple control inputs while respecting operational constraints. MPC frameworks predict system behaviour over a future horizon and compute control actions that minimise energy use and maintain comfort [100]. Studies demonstrate that MPC can reduce chilled-water plant energy consumption by up to 25% compared to traditional control approaches such as fixed-setpoint

control, rule-based or schedule-based strategies, and proportional–integral–derivative (PID) control while still maintaining overall system stability [101–103].

The application of advanced control methodologies such as Model Predictive Control (MPC), adaptive control, and machine learning-based predictive control has been increasingly explored in practical chilled water system installations. These case studies illustrate the tangible benefits in terms of energy savings, improved thermal comfort, and operational stability.

Yuan et al. present a Model Predictive Control (MPC) method to eliminate hydraulic oscillations and dynamic hydraulic imbalance in complex chilled water systems [104]. They develop a detailed hydraulic model calibrated via a Genetic Algorithm using real-time sensor data, achieving accurate parameter estimation. Unlike traditional PID controllers, their MPC adjusts valve openness and pump speeds directly from model simulations, preventing oscillations. Validated in a 22-floor hotel system, the method achieved stable flow control with less than 1% error and reduced circulation pump energy consumption by 23.3% compared to conventional control. This approach offers a practical and energy-efficient solution, though it relies on comprehensive sensor data and accurate calibration [104].

Qiu and colleagues present a multi-agent reinforcement learning approach combined with game theory for the optimal control of central chiller plants [105]. In this method, the control of chillers, pumps, and cooling towers is assigned to separate agents, which coordinate with each other to balance energy efficiency and user comfort. Using the State-Action-Reward-State-Action algorithm and a data-driven simulation based on real heating, ventilation, and air-conditioning data, the approach achieves over ten percent energy savings compared to the baseline and matches the performance of the "Win or Learn Fast – Policy Hill Climbing"

algorithm. This model-free, coordinated control method shows promise for practical HVAC optimization [105].

Huang et al. develop high-fidelity hierarchical dynamic models of chiller and boiler plants using the Modelica language to study control-related faults in large commercial buildings [106]. The models incorporate detailed physical components and control systems, enabling realistic simulation of faults such as sensor bias, leaking valves, and mistuned Proportional-Integral (PI) controllers. The hierarchical structure supports extensibility and large-scale fault scenario analysis, while co-simulation with Energy Plus captures interactions between supply- and demand-side systems. Fault impact analysis over a year-long simulation reveals that sensor bias faults in chillers (notably temperature sensor faults) significantly increase energy consumption (up to 19.8%) and unmet heating/cooling hours, while leaking valves and mistuned controllers also degrade performance and increase energy use. The study highlights nonlinear and component-interaction effects on fault impacts and provides a validated modeling framework for advancing fault detection and diagnostics (AFDD) research in HVAC systems [106].

Díaz Torres et al. compare conventional staging and a co-design approach that integrates optimal chiller loading (OCL) and optimal chiller sequencing (OCS) in the early design phase of chiller plants for hotel buildings [49]. Traditional on/off sequencing methods start chillers based on capacity but may result in inefficiencies when coupled with automatic control systems. The co-design approach optimizes chiller sequences and load distribution simultaneously to better reflect future operational conditions. Using detailed thermal load modeling and regression-based black-box models, the study evaluates six chiller configurations for a Cuban hotel across various occupancy scenarios. Results indicate that the co-design method achieves up to 24.8% energy savings and a 59.7% improvement in coefficient of

performance (COP) compared to the best symmetrical configuration selected via conventional design. This work underscores the value of incorporating control strategies in the early design process to enhance chiller plant energy efficiency and performance in the hospitality sector[49].

Zhou et al. apply association rule mining (ARM) using the Apriori algorithm to optimize operational parameters of a chiller plant in a large-scale shopping mall in Guangzhou [1]. Leveraging four years of operational data (over 850,000 records), they identify strong associations between key controllable parameters such as chilled water supply temperature, chilled water pressure differential, and cooling water supply temperature and chiller plant performance indexed by the coefficient of performance (COP). The study discretizes operational data and defines 54 typical operating conditions to extract operational rules with at least 70% confidence level. Simulation results indicate that applying these rules can reduce total chiller plant energy consumption by 13.33% in the transition season and 11.6% in summer, mainly due to improved pump efficiency. This data-driven approach offers a practical methodology to exploit large operational datasets for energy savings without relying on complex physical modeling [107].

Zulkaflī et al. present an optimization framework for the operation of a chiller plant in an academic building using Linear Programming (LP) to minimize energy consumption and electricity costs while maintaining thermal comfort [108]. The model incorporates constraints related to chillers, cooling towers, air handling units, and pumps, calibrated with real operational data. The study applied the LP model to a four-storey building with two chillers and two cooling towers, optimizing over a 10-hour air-conditioning period. Results show the optimized operation yields approximately 23% cost savings compared to the current operation, with improved coefficient of performance (COP) values (4.69 and 5.04 for the two chillers) indicating high efficiency. The framework demonstrates the potential for significant energy

and cost reductions through coordinated control of HVAC components using mathematical optimization [108].

Zhang et al. implemented an MPC strategy within a large commercial office complex to optimise chilled water supply temperature and pump operation [109]. The MPC algorithm utilised forecasts of internal loads and weather conditions to adjust chiller staging and flow rates proactively. A longitudinal monitoring period of six months demonstrated a 22% reduction in chiller energy consumption relative to conventional rule-based control [109]. Moreover, the system achieved reduced frequency of chiller cycling and enhanced temperature stability across zones, which contributed to improved occupant comfort and prolonged equipment life.

Dashen et al. deployed an adaptive control algorithm at a university campus chilled water plant that regulated chilled water flow at the zone level based on real-time sensor feedback [110]. The controller dynamically adjusted operational parameters to accommodate fluctuations in occupancy and load demand. Experimental findings indicated a 17% reduction in total chilled water plant energy consumption over one academic semester, accompanied by a notable decrease in temperature variation across the building zones, thereby enhancing thermal comfort and system responsiveness [110].

Zhao et al. propose a data-driven energy management framework for HVAC systems that integrates symbolic regression with model predictive control (MPC) to optimize energy consumption, peak power demand, and thermal comfort [111]. The framework uses only built-in HVAC sensors and weather forecast data to predict indoor temperature dynamics, avoiding the need for detailed building models or additional hardware. The authors conducted on-site experiments in an office-like laboratory, evaluating both cooling and heating operations. Results show that the proposed approach reduces energy consumption by up to 49.3% for

cooling and 73.9% for heating, while peak power demand is lowered by up to 35.1%. The framework also shortens HVAC runtime by leveraging internal heat sources during heating. These findings demonstrate that the framework can effectively improve HVAC efficiency and occupant comfort in real-world settings. Limitations include lengthy training times for symbolic regression and single-room testing, with future work aimed at multi-zone extension and faster model training [111].

2.8.3 Experimental Investigations of Chilled Water Flow Control

Experimental investigations serve as a cornerstone in the research and development of chilled water systems, particularly in the validation and refinement of numerical models and control strategies. While computational simulations provide valuable foresight into system behaviour under theoretical conditions, they often rely on assumptions and simplifications that may not fully capture the multifaceted realities of actual HVAC operations. Consequently, real-world experimental studies are indispensable for bridging the gap between theoretical predictions and practical implementation.

The primary purpose of experimental validation is to ensure that numerical models and control algorithms are not only theoretically sound but also accurate and reliable when deployed in operational environments. Models typically incorporate assumptions regarding equipment performance curves, hydraulic resistances, thermal loads, and occupant behaviours, many of which vary considerably in practice.

Furthermore, experimental investigations uncover a range of operational complexities that are difficult to simulate accurately. For instance, fouling and scaling in heat exchangers and piping can degrade system performance over time, impacting heat transfer efficiency and hydraulic flow paths. Equipment degradation, including wear in pumps and valves, affects mechanical

efficiency and reliability. These phenomena evolve gradually and are often overlooked in numerical simulations that typically assume ideal or new equipment conditions. Experimental studies thus provide critical insights into the long-term behaviour and maintenance requirements of chilled water systems.

Beyond validation, experimental investigations are crucial for assessing the robustness of control algorithms across diverse operating scenarios. By subjecting control strategies to real-world disturbances such as sensor faults, communication delays, and varying external weather conditions researchers can evaluate the resilience and adaptability of proposed solutions. This is particularly important for individual space chilled water flow control, where localised variations in demand and equipment response times can significantly affect overall system stability and energy performance.

Additionally, experiments facilitate evaluation of occupant comfort implications alongside energy efficiency. Measurements of zone temperatures, humidity levels, and occupant feedback collected during field trials provide a holistic view of system performance that numerical simulations alone cannot deliver. Ensuring that energy-saving strategies do not compromise comfort is critical for user acceptance and successful deployment.

Shakir et al. conduct an experimental investigation into how the inlet temperatures of chilled and hot water, along with the mass flow rate, influence the energy and exergy efficiencies in a prismatic adsorbent bed cooling system [112]. The study demonstrates that higher inlet temperatures improve energy efficiency but decrease exergy efficiency. The results underscore the importance of optimizing both temperature and flow rate to maximize system performance. The paper also discusses the system's potential for improving energy utilization while highlighting the complex relationship between energy and exergy efficiencies [112].

2.8.4 Case Studies and Applications in buildings

Practical case studies provide invaluable insights into the implementation and performance of individual space chilled water flow control in real-world settings. Universities and large commercial buildings often present complex thermal zoning and variable occupancy patterns, making them ideal environments to test advanced chilled water control strategies. Numerous recent studies have focused on the deployment of individual zone chilled water flow control in university buildings and commercial offices.

Almobarek et al. systematically reviews the role of predictive maintenance in chilled water systems, focusing on commercial buildings [113]. The authors explore predictive maintenance technologies, including machine learning algorithms, sensors, and IoT, for optimizing chiller operations and preventing system failures. They conclude that predictive maintenance can significantly enhance system reliability, reduce downtime, and improve energy efficiency. However, the paper is a literature review and lacks primary experimental data. While it provides a comprehensive overview, the effectiveness of specific predictive maintenance techniques across different building types is not explored in-depth, limiting its practical application in certain contexts. The study sets a strong foundation for future work but needs real-world case studies for validation [113].

Tai et al. present a novel high-temperature water cooling system that utilizes underground water cold energy for cooling purposes in northern China [114]. The study demonstrates the potential for significant energy savings by tapping into cold energy stored underground. Simulation and application results show that this system can effectively replace traditional chilled water plants, improving energy efficiency. While the theoretical model appears robust, the paper's reliance on simulation results without detailed real-world implementation limits its applicability. Additionally, the system's feasibility in different geographical contexts outside

Northern China is not addressed, which is a notable limitation for wider adoption. Nonetheless, the paper contributes valuable insights into innovative cooling strategies [114].

Gao et al. investigate the “Low Temperature Difference Syndrome” in a chilled water system of a super high-rise building, identifying and diagnosing the causes of inefficiency [115]. Their case study highlights how improper system calibration and operational errors led to performance degradation. Through detailed diagnostic tools and a multi-step analysis, the study provides actionable recommendations for optimizing system performance. The results suggest that addressing low temperature differences significantly improves overall energy efficiency. However, the study is focused on a single building and might not apply to all super high-rise buildings with varying cooling demands and system designs. Despite this, the study offers practical insights into diagnosing and mitigating common chilled water system issues [115].

Wu et al. explore strategies to improve the energy efficiency of chilled water systems in commercial buildings [116]. Their case study demonstrates the effectiveness of energy-saving technologies, such as variable speed pumps and optimized control algorithms, in reducing energy consumption without compromising cooling performance. The study concludes that integrating these technologies can lead to a reduction in energy costs by up to 20%. However, the paper primarily focuses on energy efficiency improvements, without fully addressing the operational challenges associated with implementing these technologies across different building types. It offers valuable recommendations but would benefit from additional case studies in diverse environments to assess scalability and adaptability[116].

Wang et al. review several case studies on energy recovery and efficiency enhancements in chilled water systems [117]. The authors explore technologies like heat exchangers and thermal storage systems that can capture waste heat and reduce the overall energy footprint of

chilled water plants. The study finds that these approaches lead to substantial energy savings, with some systems reporting reductions in energy use by over 30%. While the paper offers useful lessons from real-world examples, it does not sufficiently explore the initial investment costs and the long-term maintenance requirements of these systems. Additionally, the scalability of such solutions in buildings with limited space or lower cooling demands remains unclear. The study is valuable for understanding energy recovery in chilled water systems but needs to consider the broader economic implications of such solutions [117].

Coffey et al. delve into the application of model predictive control (MPC) for a campus chilled water system integrated with thermal storage [118]. This paper presents a significant innovation in controlling the operations of large, chilled water systems, using predictive control to optimize energy use and reduce operating costs. Through extensive testing and simulation, the study shows how the MPC can be applied to adjust the charging and discharging schedules of thermal storage tanks, which are crucial for achieving peak-load shifting. The results suggest that MPC can reduce energy consumption by up to 20%, making it a promising tool for large-scale building systems. However, the study is specific to campus-scale installations, and its applicability to other types of buildings with different thermal storage capacities or heating/cooling needs remains unclear. The findings contribute significantly to operational energy optimization but require broader validation across diverse building types [118].

Almobarek and Mendibil provide a systematic literature review of predictive maintenance (PM) strategies for chilled water systems in commercial buildings [113]. The paper explores various techniques, including machine learning algorithms, condition monitoring, and fault detection methods, to predict equipment failure before it occurs. This review highlights the growing importance of implementing PM in large-scale HVAC systems to extend equipment life and reduce downtime. The study found that predictive models, when applied correctly,

could optimize maintenance schedules, resulting in significant cost savings and enhanced system performance. The study, however, lacks experimental validation of the proposed PM methods and only synthesizes existing work. Further research and real-world case studies would be necessary to test these theoretical models in practical applications [113].

Gao et al. investigate dynamic modeling and performance analysis of chilled water systems used in buildings [119]. Their study includes a detailed review of various system configurations, control strategies, and energy performance metrics, aiming to understand how different design and operational parameters affect system efficiency. The authors demonstrate the importance of dynamic simulations in assessing system performance under varying load conditions. Through case studies of several buildings, the study shows how optimized control strategies can reduce energy consumption by up to 25%. Despite the valuable insights provided by the modeling, the study is primarily theoretical, and real-world validation of the dynamic models is not fully addressed. Future work should focus on empirical testing of the proposed models in live systems [119].

Xie et al. present a detailed case study on energy efficiency improvements in a commercial building's chilled water system [120]. The paper analyzes various operational adjustments, including flow rates, equipment performance, and energy consumption patterns, to reduce overall system energy usage. By employing optimization strategies and using advanced control systems, the authors show that significant savings (up to 18%) can be achieved in large commercial buildings. The paper offers practical insights into improving the efficiency of chilled water systems in real-world settings. However, the study does not account for external factors such as building design or regional climate conditions, which may influence the generalizability of the results. The authors suggest that more case studies are needed to verify the findings across diverse commercial environments [120].

He et al. proposes the use of genetic algorithms (GA) to optimize the operation of chilled water systems in large-scale buildings [121]. The study develops a GA-based optimization model to enhance the system's energy efficiency by adjusting parameters like pump speeds and chiller loads. The authors demonstrate that using GA leads to better load balancing and energy savings, achieving a reduction of up to 12% in energy consumption. The study's strength lies in its computational approach, which allows for real-time optimization. However, the study is focused on theoretical simulations and does not provide real-world validation. Moreover, while GA optimization is effective, it may require significant computational resources for real-time implementation, making it more suitable for research and development rather than immediate practical deployment [121].

2.9 Gap in Chilled Water Flow Control

The gaps in chilled water flow control within the HVAC industry present substantial opportunities for energy savings. Addressing these issues requires a multi-faceted approach involving the adoption of advanced technologies, integration strategies, and the creation of benchmarks. Future research should focus on developing practical, scalable solutions for these challenges, emphasizing real-world applications and long-term sustainability.

The energy savings potential of variable flow technology in chilled water systems is well-documented although underexploited. Numerous current systems continue to function on a continuous flow basis, which is less efficient [63]. Retrofitting antiquated systems with variable speed pumps and sophisticated controls often face obstacles, including elevated expenses and operational interruptions [61].

A retrofit project in a commercial building in New York demonstrated that upgrading to variable flow pumps reduced energy consumption by 30%. However, the initial cost and the

downtime during installation were significant, deterring similar initiatives in comparable facilities [61].

Control techniques often inadequately respond to dynamic fluctuations in cooling requirements. Most chilled water systems lack predictive control algorithms capable of adjusting flows based on real-time data [65]. This leads to inefficiencies and superfluous energy usage [56].

An office complex in San Francisco implemented a predictive control system for its chilled water flow, which adapted to varying occupancy levels and weather conditions. This system reduced cooling-related energy consumption by 25% but required substantial investment in sensors and software development [56,65].

Chilled water systems are often inadequately connected with comprehensive building management systems, hindering optimum energy management of the whole structure [57]. Efficient integration may significantly improve energy efficiency across all building systems. [59]. Integration of chilled water flow control with the BMS in a high-rise in Chicago allowed for coordinated operation with other HVAC components, achieving a 20% reduction in total HVAC energy usage. However, the complexity of system integration posed challenges in terms of technical expertise and system compatibility[59].

Advanced metering and accurate sensors are essential for efficient chilled water flow regulation; nonetheless, their implementation is hindered by expenses and intricacy [64]. .Optimising chilled water flow is less efficient without precise data [59]. A retrofit in a university building with advanced metering and sensors enabled detailed monitoring and control of chilled water usage, leading to a 15% improvement in energy efficiency. Despite

these gains, the upfront cost and maintenance expenses were significant barriers to wider implementation [59].

The lack of standardised standards and best practices for chilled water flow regulation across diverse climates and building types complicates the consistent assessment and enhancement of system performance[62]. Setting explicit criteria may direct the sector towards more efficient designs [58]. The development and implementation of a benchmarking protocol for chilled water systems in a commercial district in Tokyo helped reduce discrepancies in system performance. However, tailoring the benchmarks to accommodate diverse building types was a complex and time-consuming process [58].

While numerous studies demonstrate the energy-saving potential of individual space flow control, many focus on isolated aspects such as control algorithm development or experimental validation in limited settings. Comprehensive investigations that integrate building thermal dynamics, hydraulic network complexities, and occupant behaviour remain scarce. Furthermore, most research concentrates on short-term experiments or simulations, leaving long-term operational impacts and maintenance challenges underexplored

Another gap exists in the consideration of retrofit applications in existing buildings with legacy infrastructure, where integration complexities and cost constraints limit adoption. There is also a need for standardised benchmarking frameworks to objectively compare different control strategies across diverse building types and climatic zones.

The gap between numerical modelling and practical implementation highlights the need for integrated approaches combining detailed simulations with thorough experimental validation. Such hybrid methodologies enable model calibration, reliability assessment, and real-world adaptation of control algorithms. Integrated approaches can also facilitate the exploration of

system behaviours under varying environmental conditions and occupant patterns that are difficult to replicate solely through experiments or simulations.

By coupling numerical and experimental methods, researchers can more accurately predict energy savings, system robustness, and occupant comfort outcomes, supporting confident decision-making and wider adoption of individual space flow control technologies.

Scalability of individual space flow control systems from pilot studies to large campuses or commercial complexes presents significant challenges. The increased complexity of network hydraulics, sensor and actuator deployment, and data management require robust control architectures capable of handling high-dimensional inputs and outputs. Ensuring control robustness amidst sensor faults, communication delays, and varying occupant behaviour further complicates system design.

Real-time implementation demands efficient algorithms that can process large datasets and adjust control actions swiftly without compromising stability or comfort. These challenges necessitate research into distributed control frameworks, machine learning integration, and fault-tolerant control systems.

This research aims to bridge some gaps by developing an integrated numerical and experimental framework tailored to the University of Nottingham Malaysia's chilled water plant. By combining detailed system modelling with field measurements, it will advance understanding of individual space flow control impacts on energy consumption and operational efficiency.

Chapter 3: Research Methodology

3.1 Introduction

This study employs an experimental and numerical-based approach to analyse and compare the operation and performance of chilled water plant serving a multi-zone office building based on two chiller pump flow control strategies: namely, a predictive-adaptive flow control approach and a constant flow control method. The objective is to evaluate the benefit of both strategies in meeting indoor comfort requirements while minimising energy consumption and carbon footprint. The numerical modelling technique will be applied to simulate the behaviour of the chilled water plant under both control approaches using weather data representative of the Kuala Lumpur climate.

The research begins with the collection of relevant data, including environmental parameters, building specifications, and system performance metrics. A detailed description of the case study building and its HVAC system follows, providing context for the experimental analysis of its thermal performance. The methodology then advances to the development of a thermal equivalent model of the building, which serves as the basis for integrating a chilled water plant system. Model validation and calibration are conducted to ensure accuracy, aligning the simulated system behaviour with real-world performance.

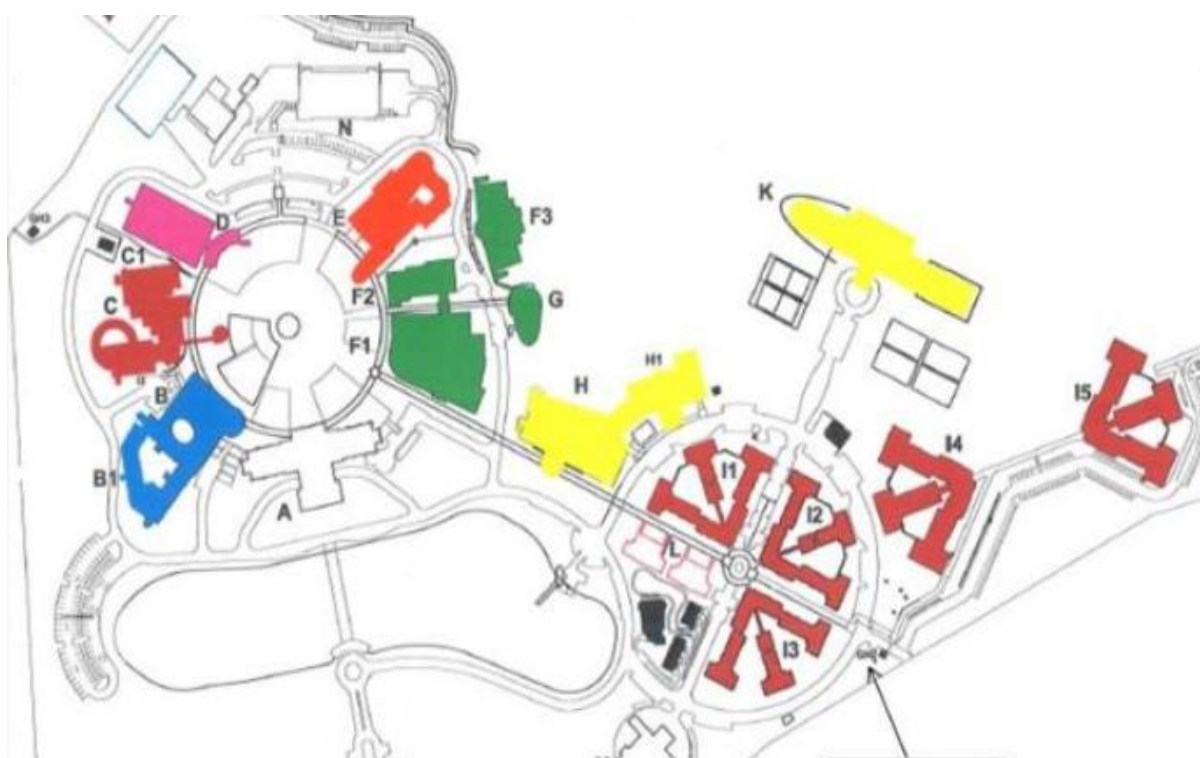
A key focus of the study is the development and implementation of an adaptive chilled water flow control strategy, designed to enhance system efficiency under varying operational conditions. The system's performance was first evaluated based on the existing constant flow control approach to establish a baseline for comparison. The benefits of the developed adaptive

flow control strategy were then assessed relative to the current operation of the chilled water plant.

3.2 Description of case study building and chilled water plant

This research is conducted to assess the energetic performance of the chilled water plant system at the University of Nottingham Malaysia. The university comprises nine (9) main buildings named based on the colour paint of the block that are cooled by a centralised chilled water plant system. The approximate geometry and orientation of each building, represented by letters A to H, as described in Figure 3.1. is shown below.

This study focuses specifically on evaluating the effectiveness of the chilled water plant in Block B the Blue Building. Block B was selected to demonstrate the proof of concept of the research since its occupancy patterns, cooling demand, is a representative of a typical office building. The study aims to analyse the thermal performance of the building in relation to the operation of the chilled water plant and assess potential improvements through adaptive chilled water flow control.



Block / Code	Colour	Description / Function
BLOCK A	White building	Central Administration
BLOCK B	Blue building	Faculty of Science & Faculty of Engineering
BLOCK C	Purple building	Faculty of Engineering & Faculty of Science
BLOCK E	red building	Faculty of Engineering
BLOCK F	Green building	Faculty of Arts & Social Science
BLOCK H	Yellow building	Information Services – ICT Support

Figure 3.1. The layout of the main buildings (based on colours) of the University of Nottingham Malaysia

The chilled water plant consists of a chiller connected to produce chilled water supply at a low temperature of approximately 7°C. This chilled water is then redistributed to all air handling units in Block B through a robust network of pipes and diverters, as illustrated in Figure 3.2. To effectively circulate the chilled water throughout the distribution network, the current installation is equipped with chilled water pump.

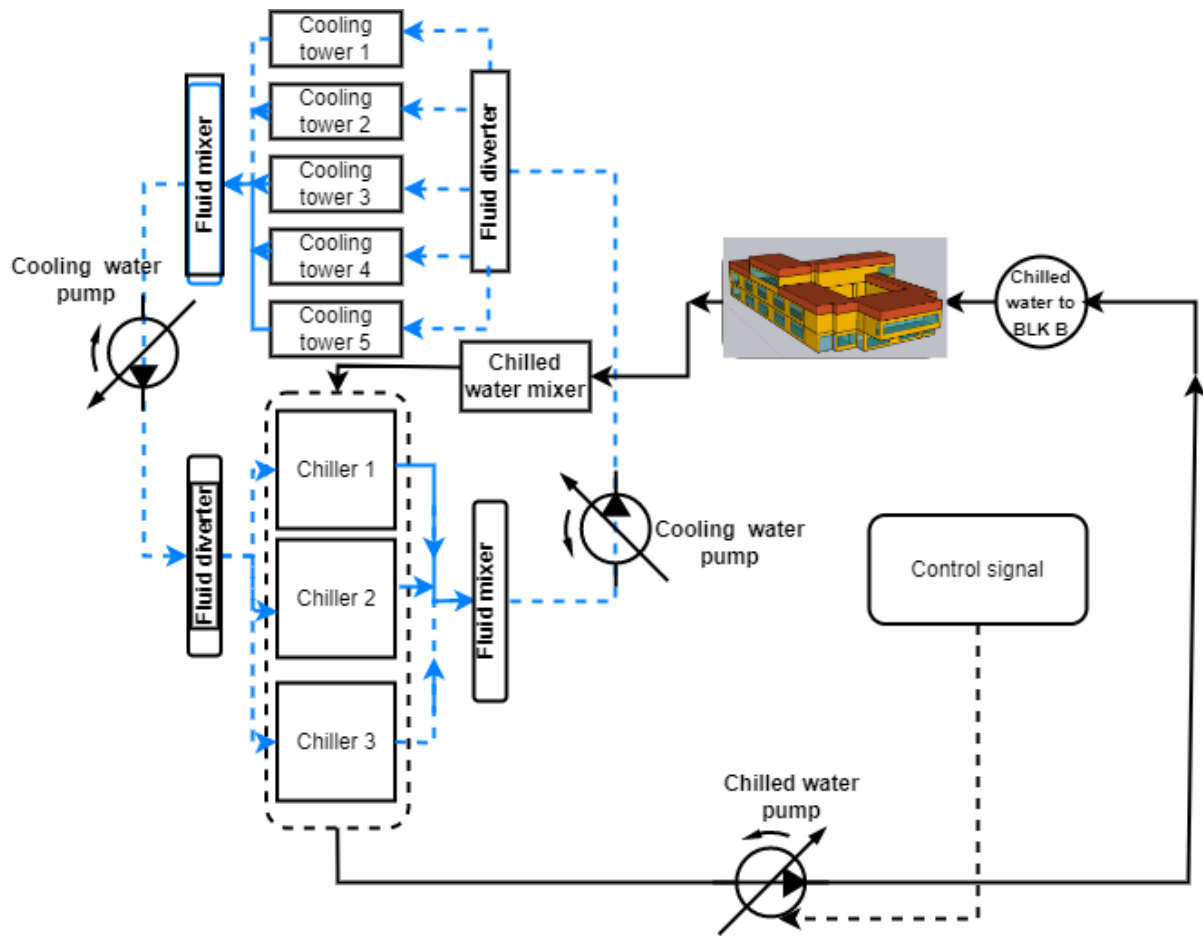


Figure 3.2. Schematic of the building showing the link to cooling system

On the cooling water side, heat rejection is managed by five cooling towers, which work collectively to maintain optimal chiller operation and ensure efficient heat dissipation. Within the block, air handling units (AHUs) are responsible for distributing the chilled water to various thermal zones, ensuring consistent indoor environmental conditions. The details of the HVAC system, specifically the chilled water distribution within Block B, are illustrated in Figure 3.3.

For this network, the chilled water at 7°C enters block B and is redistributed to various air handling and fan coil units as shown in Figure 3.3. Block B has 18 thermal zones, with 12 air handling and fan coil units connected to cool the zones as demonstrated in Figure 3.4

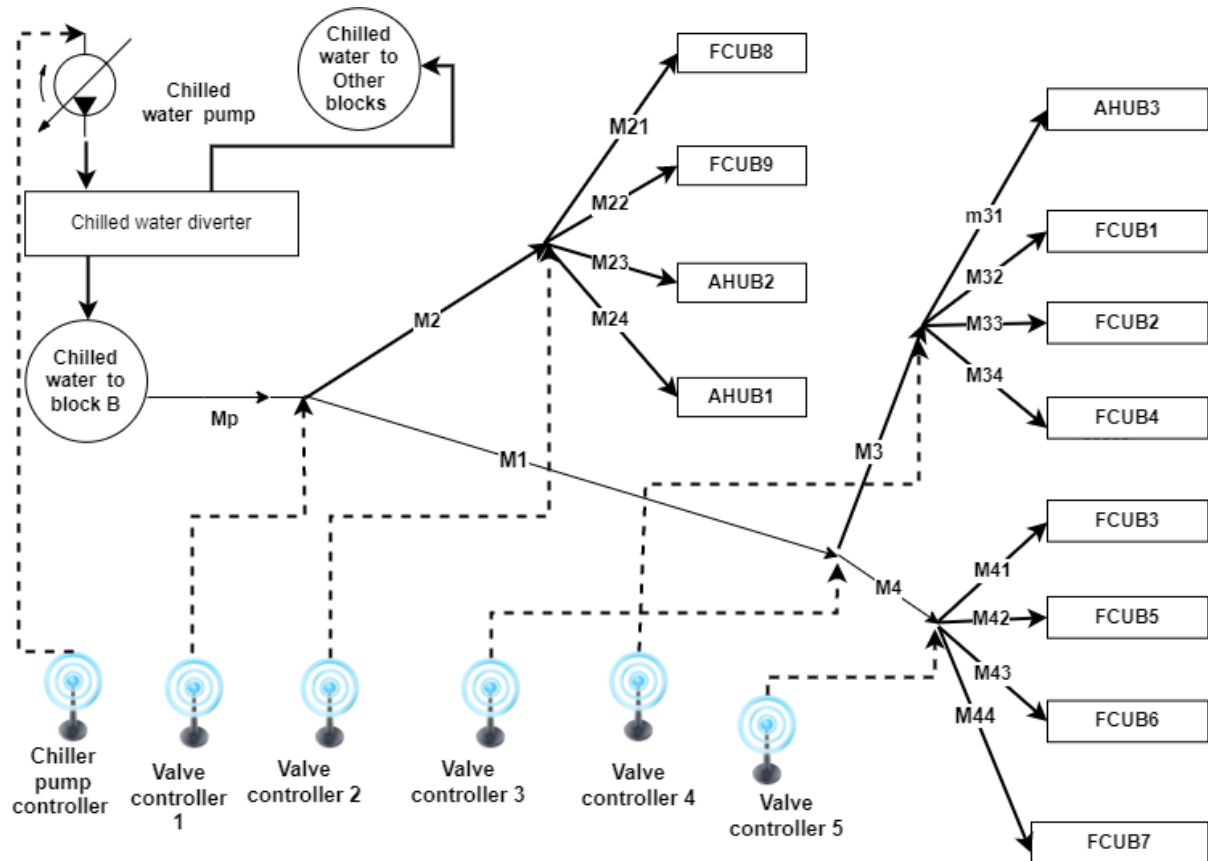


Figure 3.3. The distribution of the chilled water to the Air handling Units in block B

Furthermore, the detailed schematics of the thermal zones in Block B, including their connection to air handling units (AHUs) and fan coil units (FCUs), are shown in Figure 3.4. This schematic representation provides insight into the chilled water distribution within the building and highlights the interaction between different cooling components in maintaining thermal comfort. The HVAC cooling system is modelled to reflect this network.

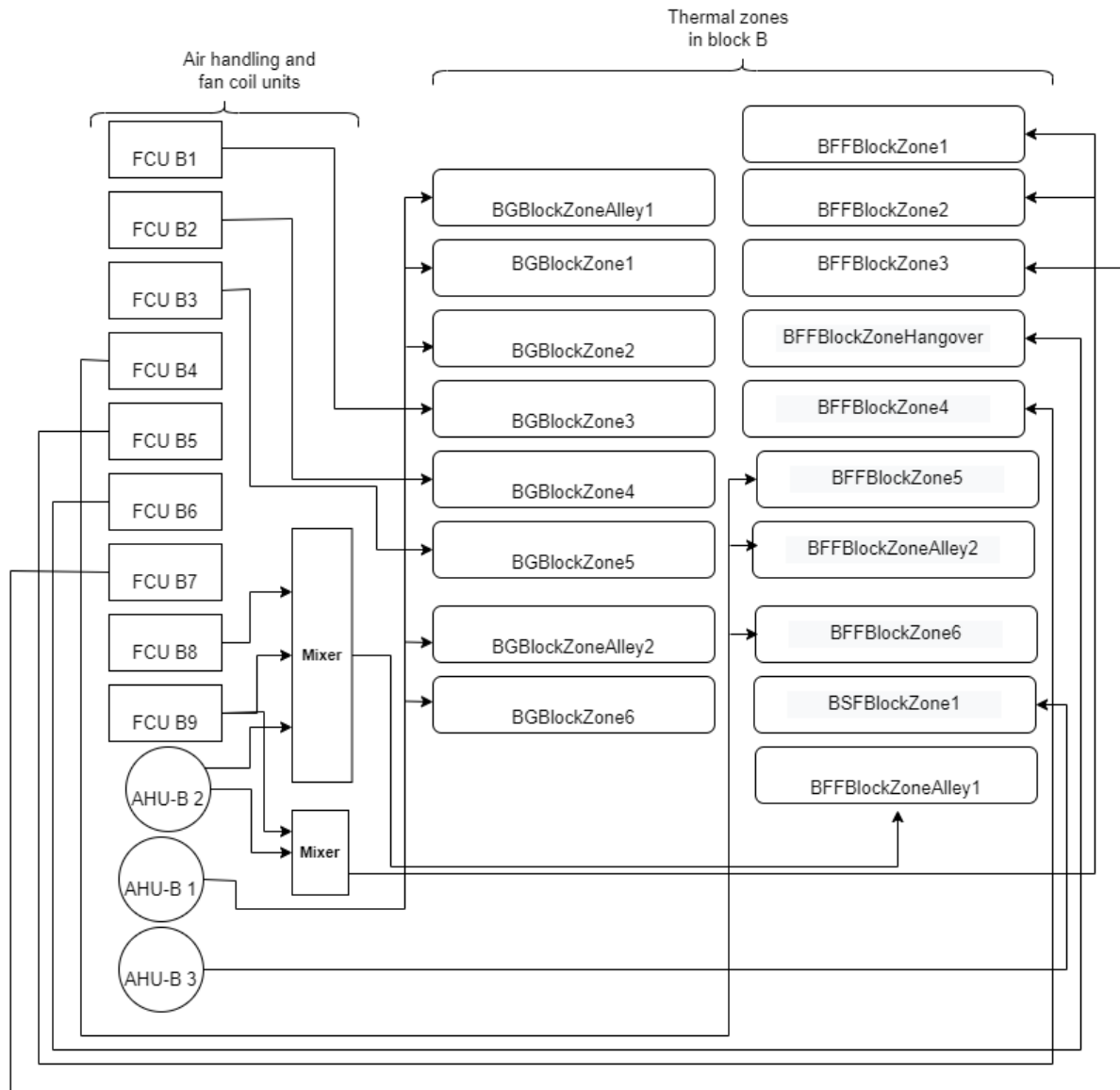


Figure 3.4. Schematics of the thermal zones in Block B, and their connection to (AHUs)

3.3 Data collection and system specifications

A comprehensive data collection process was conducted to ensure accurate representation of the case study building and its chilled water plant system. This process involved gathering architectural and mechanical specifications, as well as operational data, to facilitate precise thermal modelling and system analysis.

Building Geometrical Specifications: The architectural drawings of the university buildings were obtained from the estate unit and carefully studied to extract key geometrical specifications. These specifications included window dimensions, roofing material types, block types and dimensions, building orientation, and the sizes of different sections within each block. To streamline the thermal analysis, the dimensions from the architectural drawings were reinterpreted into thermal equivalent zones, effectively segmenting the building into areas with similar thermal characteristics. In addition, material composition details from the working drawings were analysed, and the material properties were estimated using standard references from the Handbook of Building Materials, as summarised in Table 3.1.

Table 3:1. Building material thermal properties

Material	Thermal conduction	Heat Capacity	Density
	(kJ/mK)	(J/kg.K)	(kg/m³)
Clay Brick	4.70	0.80	1700
Concrete	1.80	1.05	2400
Ceramic tiles(porcelain)	5.40	1.05	2400
Concrete roof tiles	1.80	0.80	2400
Plaster	0.65	0.95	700
Single glazed window	3.78	0.84	2500

These material properties are crucial for accurately determining heat transfer rates, thermal mass, and insulation performance in the building simulation models.

Operational and Environmental Data: Beyond structural and mechanical specifications, data on real-world building operation and occupant behaviour were also recorded. Information regarding the number of occupants, occupancy schedules, lighting usage patterns, and equipment operational schedules was gathered through direct observation and systematic recording using a data acquisition form. These inputs are essential for accurately modelling internal heat gains and understanding the dynamic thermal load variations within the building.

3.4 Model Development and Validation

3.4.1 TRNSYS building model validation

To validate and calibrate the formulated model for annual performance simulation and evaluation, experimental measurements of the thermal performance of Block B were conducted. A Raspberry Pi-based data acquisition system equipped with sensors was deployed to measure hourly temperature and relative humidity within selected thermal zones of Block B. These real-time readings were logged and automatically recorded in a Google Sheet for continuous monitoring and analysis. Figure 3.5 below illustrates the approach used in this phase of the study.

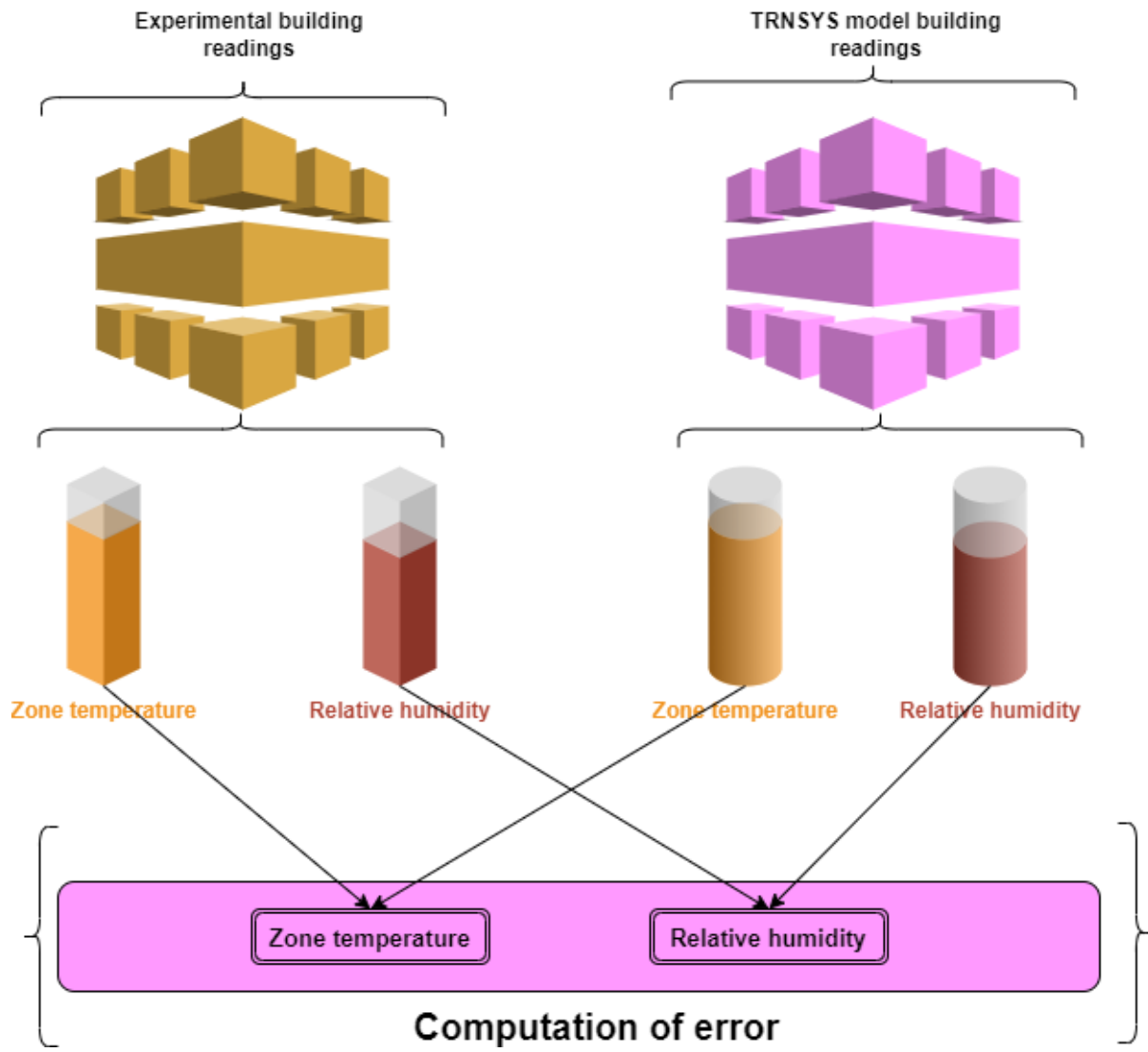


Figure 3.5. Validation approach using mean square error

The comparison between the simulated performance of the building model and the actual experimental readings was conducted using the Mean Square Error (MSE) statistical tool. The error evaluation for validating the model against experimental data is conducted using the Mean Square Error (MSE) equation as expressed below in equation (3.1)

$$MSE = \frac{1}{N} \sum_{i=1}^N T_{measured,i} - T_{simulated,i} \quad (3.1)$$

where:

N = total number of observations, $T_{measured}$, is experimentally measured temperature at time step, $T_{simulated}$, is temperature predicted by the simulation model at time step, MSE is an effective metric for quantifying deviations between predicted and observed values, ensuring a robust assessment of model accuracy. The level of acceptance for validation was set at an MSE threshold of less than 30%, following standards used in similar studies[[]]. This threshold ensures that the model remains within an acceptable margin of error for reliable performance prediction. A low MSE value indicates that the simulated model closely replicates real-world conditions, affirming its reliability.

3.4.2 Experimental Setup and Numerical Model Validation

In this study, a systematic approach was adopted to validate and calibrate a numerical model of the chilled water-cooling system integrated with the building HVAC system. Initially, a simplified small-scale experimental facility was established to represent the dynamic thermal behaviour of the building cooling load and the corresponding chilled water system operation under controlled conditions.

The experimental setup comprised of a physical prototype of the setup situated in a 160-meter square floor area and a 3 m high building located on the first floor of a commercial premises in Petaling Jaya, Kuala Lumpur. This space was equipped with a fully instrumented HVAC system designed to mimic the operation of the real chilled water plant and cooling distribution network. The system included a dual-coil chiller, centrifugal pumps, constant-speed fan coil units and Belimo™ Energy Valves equipped with integrated Class II thermal energy meters for precise measurement of enthalpy-based energy transfer as shown in Figure 3.6.

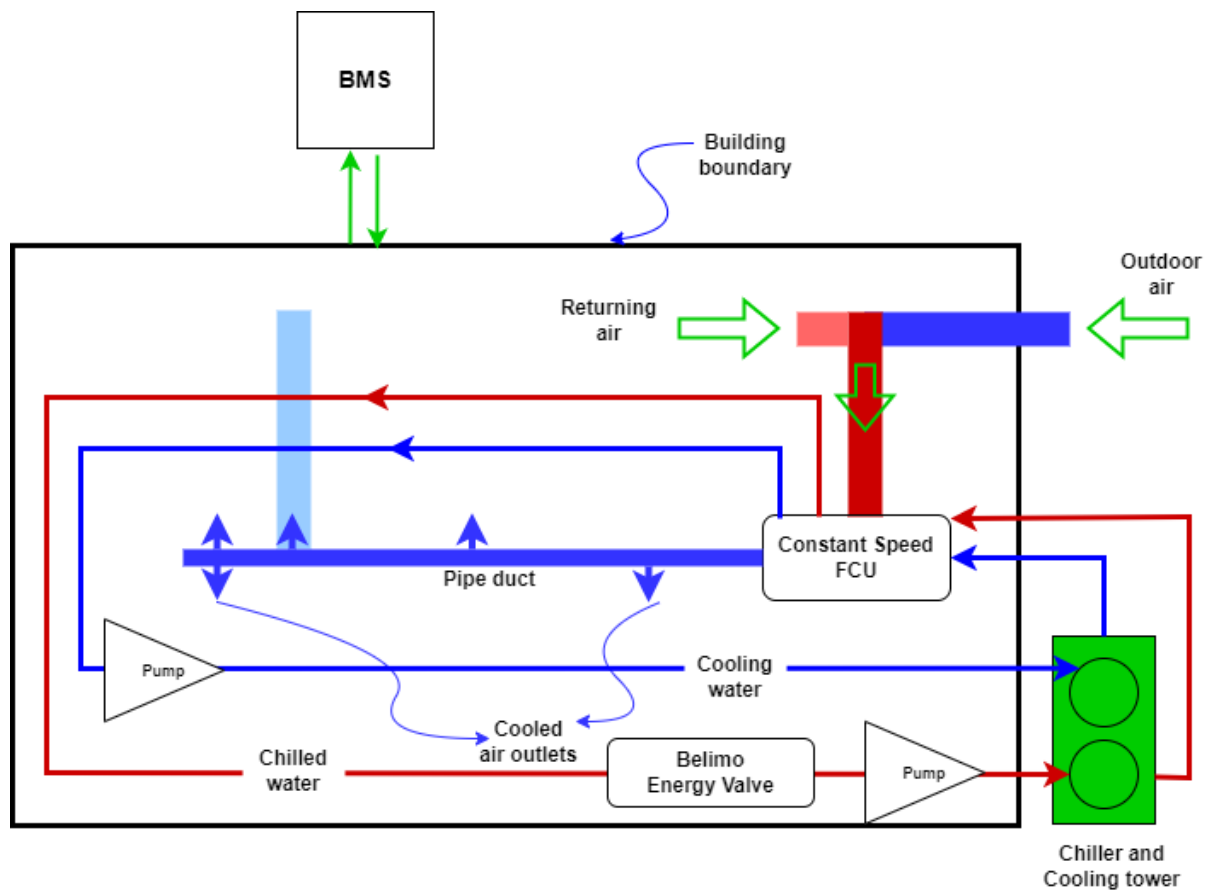


Figure 3.6. Schematic illustration of the experiment setup

As seen from Figure 3.6, the ductwork, spanning 16.8 meters, facilitated conditioned air distribution to the test zone, while a Building Management System (BMS) provided supervisory real-time control and data acquisition functionalities. Chilled water circulation within the pipe network was facilitated by a variable-speed pump, strategically installed on the chilled water return line near the chiller inlet to optimize hydraulic efficiency. The Belimo™ Energy Valves, as seen in Figure 3.7 and Figure 3.8 positioned upstream of the pump on the return line, enabled accurate measurement and control of chilled water flow and energy consumption.

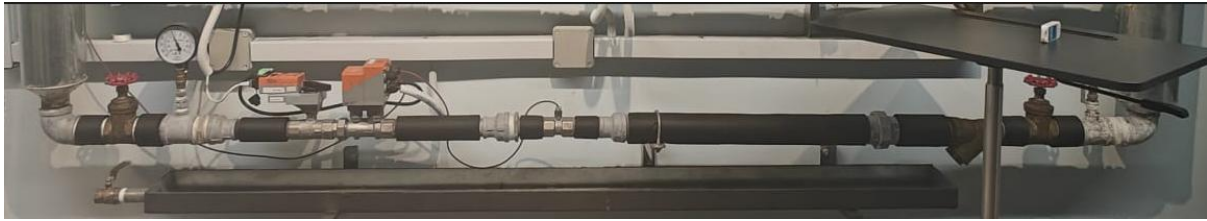


Figure 3.7. Photo image of the Belimo™ Energy Valve in the real setup as shown in Figure 3.6

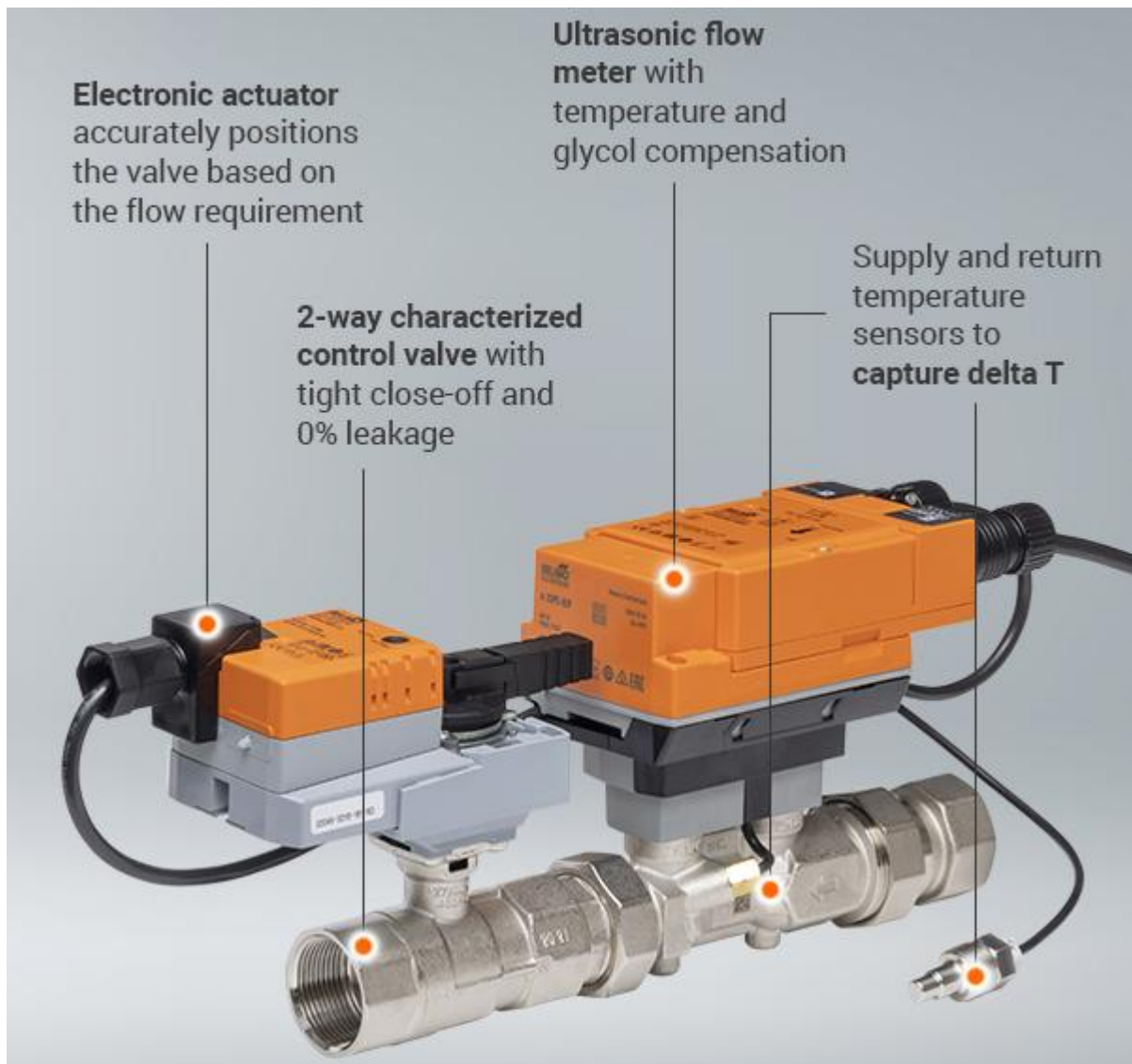


Figure 3.8. Detail description of the Belimo™ Energy Valve

The BMS allowed for setpoint adjustments, flow rate control, and performance monitoring throughout the experimental procedure. Figure 3.9 shows the interface of the BMS system

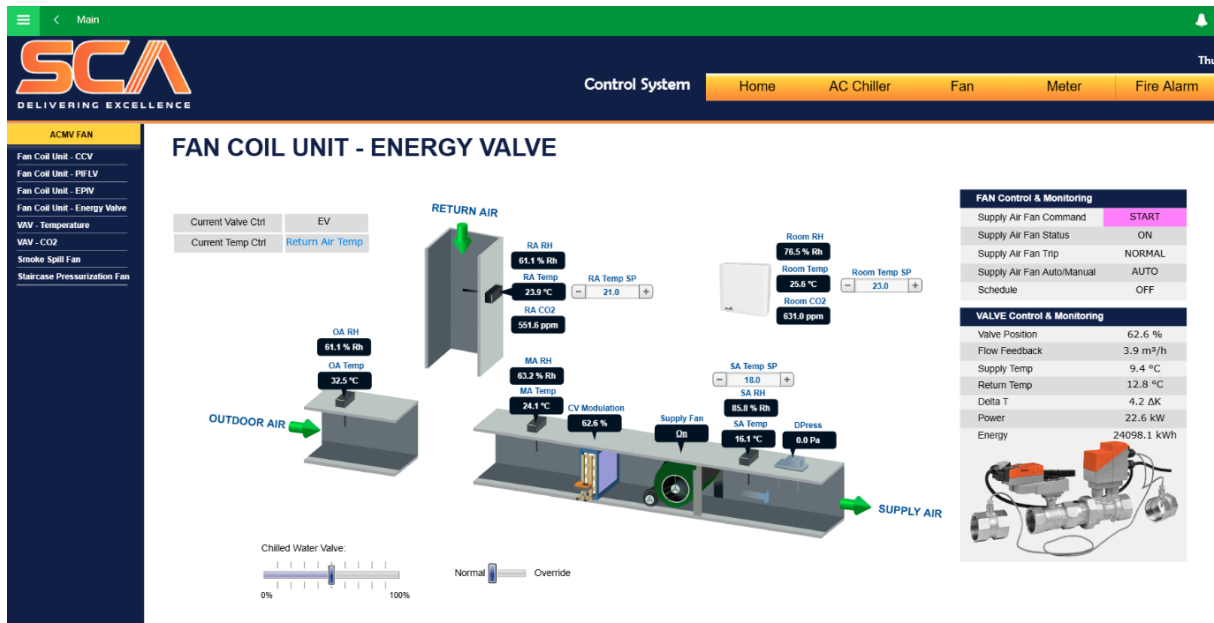


Figure 3.9. Interface and environment of the BMS showing all the tabs for input to control the chiller

During the experiment, the inlet air temperature and cooling temperature setpoints were fixed at 17 °C and 24 °C, respectively, using the BMS interface. These setpoints were held constant to ensure a stable and controlled operating environment, eliminate external thermal disturbances, and allow the performance assessment to focus solely on the effect of flow variation.

Meanwhile, the chilled water flow rate was systematically varied from 2.0 m³/h to 5.0 m³/h in increments of 0.5 m³/h. This stepwise variation provided a structured way to observe how incremental changes in flow rate influence heat transfer, cooling capacity, and overall system behaviour. The 0.5 m³/h interval ensured sufficient resolution for analysing performance trends without causing abrupt operational shifts, while the chosen range (2.0–5.0 m³/h) represents typical operating limits of the system under realistic cooling loads.

For each flow rate adjustment, the system was allowed to stabilize before empirical data collection commenced. Temperature measurements across the chiller were recorded using calibrated thermocouple-integrated data loggers (U-NIT UT325F and Elitech RC-5) (Figure 3.10), which complied with ISO/IEC 60584-1 standards, ensuring an accuracy of $\pm 0.5^{\circ}\text{C}$.



Figure 3.10. Temperature and wind condition measuring device used during the experiment

Simultaneously, flow rates and supply air temperatures were captured using a thermal anemometer (Testo 405i). Additional system parameters including chiller compressor load (kW), pump hydraulic power (kW), and aggregate electrical consumption (comprising chiller, pump, and fan power) were continuously monitored as demonstrated in Figure 3.8.

This physical experimental setup served as a proof-of-concept platform to validate a simplified numerical model developed using the TRNSYS simulation environment. The initial small-scale model represented the building as a single thermal zone, capturing its dynamic cooling load profile while integrating an equivalent chilled water and HVAC system to reliably meet this load as shown in Figure 3.11.

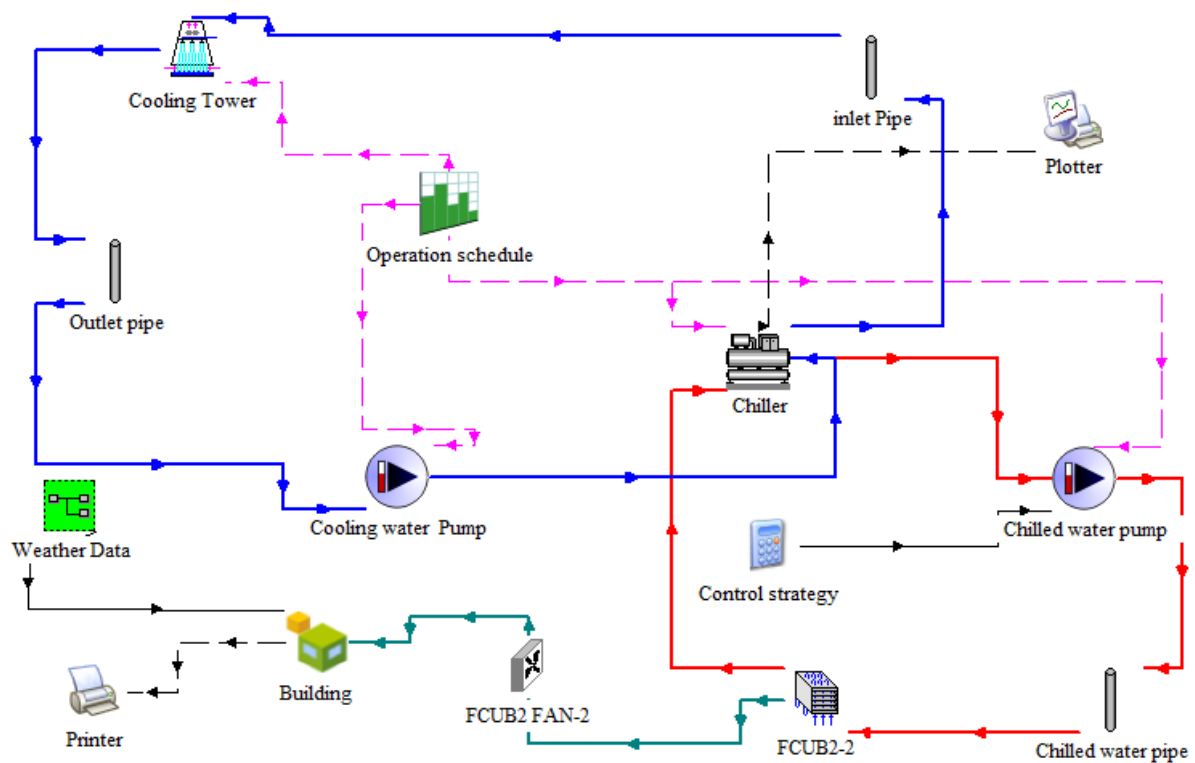


Figure 3.11. Simple TRNSYS model of chilled water plant used for validation of numerical model

The model was then simulated based on the chilled water pump flowrate varying from $2\text{m}^3/\text{h}$ to $5\text{m}^3/\text{h}$ using Kuala Lumpur's typical meteorological weather data. Energy consumption and thermal performance results generated by the numerical model were compared against empirical data from the experimental setup to calibrate and validate the model's accuracy. Upon successful validation and calibration of the simplified single-zone model, the study progressed to develop a more detailed and complex numerical model representing the actual multi-zone building configuration and the full chilled water plant system. This enhanced model

incorporated the building's geometric and thermal heterogeneity and was used to perform comprehensive annual performance simulations and evaluations. The validated complex model enabled the assessment of system behaviour under realistic dynamic thermal loads and control strategies, providing robust insights into potential energy savings, thermal comfort improvements, and operational efficiencies achievable through advanced chilled water flow control.

3.5 System Modelling

3.5.1 Building and HVAC Modelling

The thermal equivalent modelling of the case study buildings was formulated using a structured approach to accurately represent the geometry, material properties, and operational characteristics of block B. The architectural dimensions from the building's design drawings were first recreated using SketchUp software as seen in Figure 3.12. After the 3D model was developed, it was exported to the TRNSYS simulation environment, where additional thermal and operational parameters like the heat capacity, thermal conductivity, and insulation properties of construction materials were assigned based on standard material databases were incorporated. Equipment and lighting heat gains were integrated to reflect real-world energy consumption patterns. The impact of occupants on internal heat generation was modelled using measured occupancy schedules. HVAC system controls, air exchange rates, and cooling setpoints were defined to match actual building operations. This modelling process ensured that the thermal behaviour of the buildings was accurately replicated, forming the foundation for energy performance simulations and cooling load evaluations.

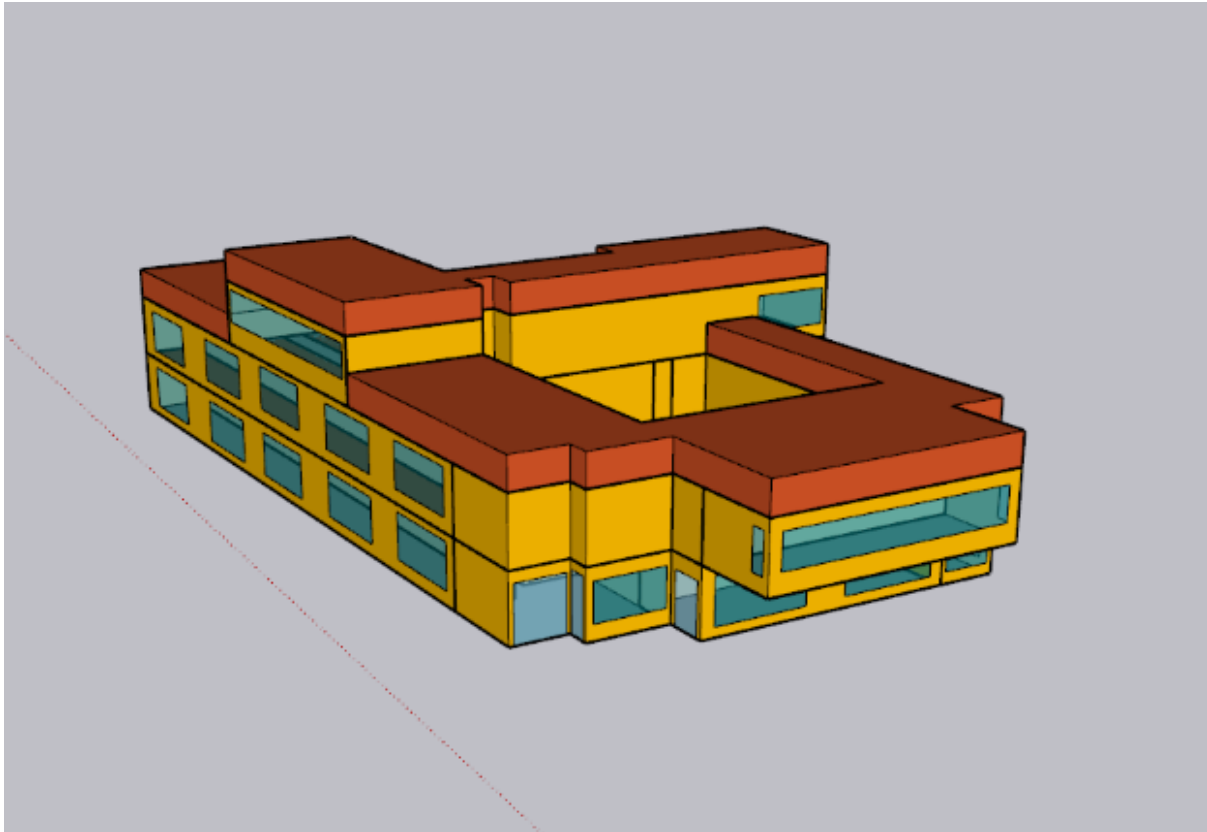


Figure 3.12. Thermal equivalent of architectural building with different zones created using SketchUp

3.5.2 Chilled water plant model

The chilled water plant is a central component of the building's cooling infrastructure, designed to maintain comfortable indoor temperatures by efficiently removing heat from various zones. The system is composed of two main loops working in harmony: the condenser water loop in blue lines and the chilled water loop in red lines as shown in Figure 3.13. The condenser water loop begins with five cooling towers, each responsible for rejecting heat into the atmosphere. All five towers are supplied with fresh make-up water from a shared reservoir that compensates for evaporation and other losses. The cooled water from each tower flows out and is combined through a mixer valve. This mixed stream is then directed toward the condenser water pumps. This pump pushes the water into the chiller, where it absorbs the heat extracted from the chilled water loop.

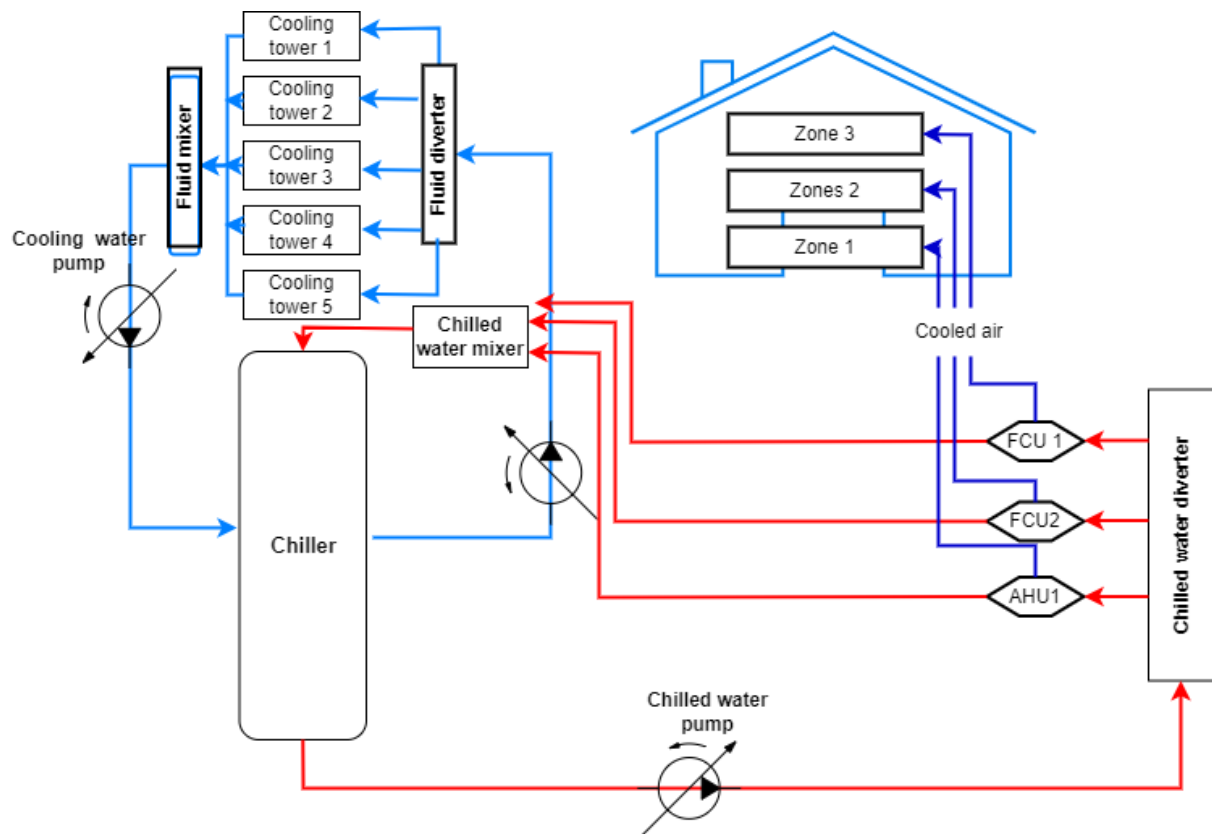


Figure 3.13. Schematic of the chilled water plan connected to the Air handling units

As the condenser water picks up this heat, its temperature rises. The heated water from the chiller is then directed back to the cooling towers. Just before it enters the towers, this stream is divided into five paths one for each cooling tower allowing for effective and balanced heat rejection.

In parallel, the chilled water loop handles the actual cooling of the building. After being cooled to approximately 7°C inside the chillers, the chilled water is pushed out by the supply pump. It travels through an intricate piping network to various air handling units (AHUs) and fan coil units (FCUs) distributed throughout the building. These units draw in warm air from the different zones and pass it over chilled water coils, allowing the chilled water to absorb the heat. This process cools the air before it is recirculated back into the zones. As a result, the temperature of the chilled water increases. This now-warmed water is returned through a

separate set of three pumps, which feed it back into the chillers. Here, the water is cooled once again to 7°C, and the cycle repeats. in Figure 3.13. illustrates the full network of the chilled water plant, clearly showing its interaction with the AHUs, FCUs, chillers, cooling towers, and pumps, thereby providing a complete understanding of how the system supports the building's climate control needs

The chilled water plant along with the HVAC system integrated into the building as shown in Figure 3.13. were modelled within the TRNSYS Simulation Studio, where each component of the system in Figure 3.13. was carefully represented using predefined simulation components, known as "Types." and connected to each other to interact based on the flow of information as depicted in Figure 3. 13. Figure 3.14 is the TRNSYS model of the system represented in Figure in Figure 3.13. while Figure 3.15 is the exploded view of the macro unit (Air Handling Unit) of the TRNSYS model in Figure 3.14.

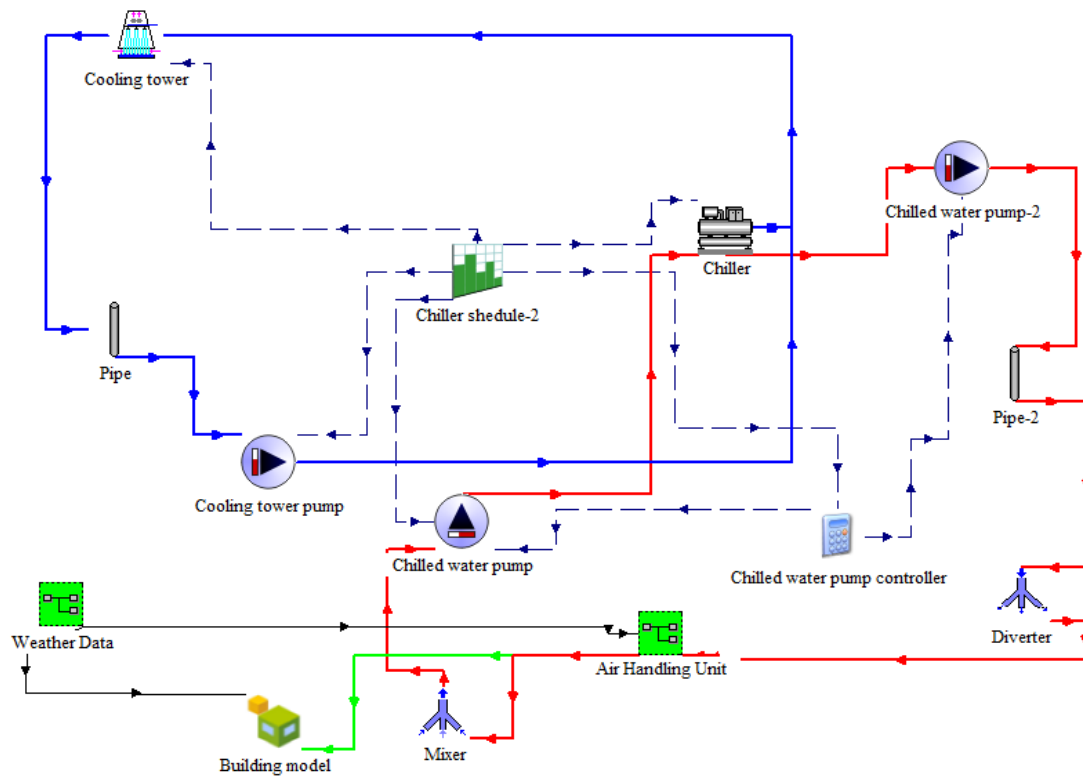


Figure 3.14. The TRNSYS model of the HVAC system to cool the building

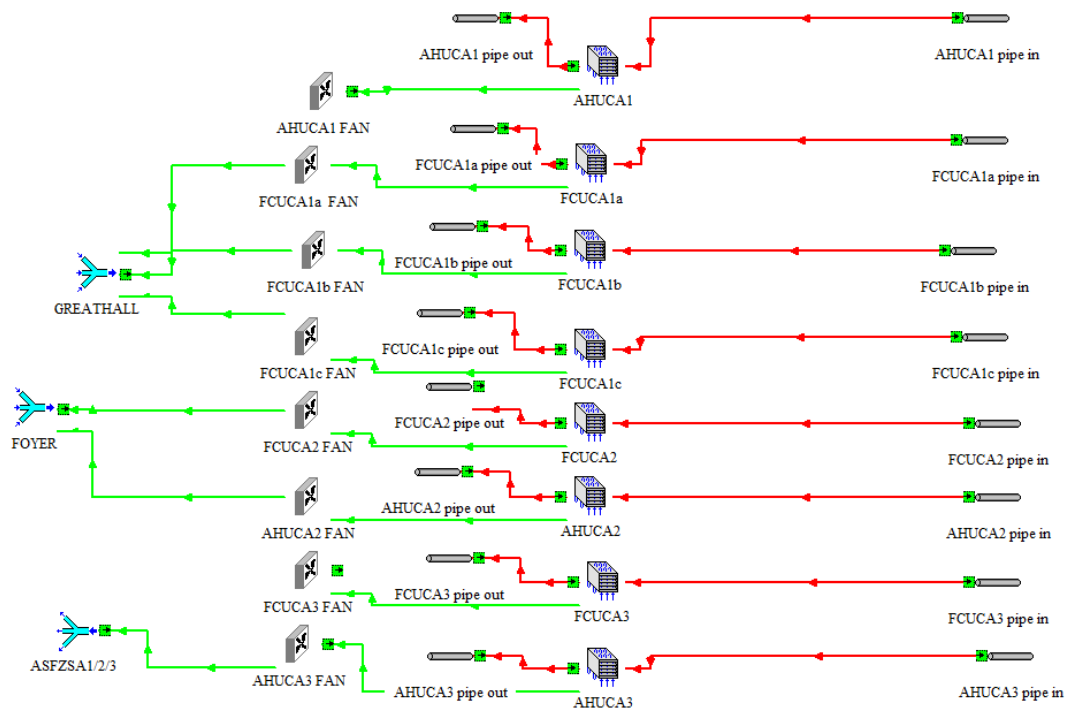


Figure 3.15. Exploded view of the air handling unit showing the various AHUs and FCUs

Tables 3.2 show the various subcomponents of the TRNSYS model used to simulate the performance of the entire system and their function in the model.

Table 3:2. Function of the TRNSYS “Types” of the chiller water plant in the model

SN	Component	TRNSYS Type	Function
1	Chillers	Type 107	Simulates the cooling capacity and energy consumption of the chillers based on manufacturer performance curves.
	Water Pumps	Type 114	Models pump flow rate, power consumption, and efficiency
	Cooling Towers	Type 510	Simulates evaporative cooling and heat dissipation under varying environmental conditions.
	Forcing function	Type 14	Is used to introduce external, time-dependent data into a TRNSYS simulation. This component is commonly used to represent schedules or weather data that drive the behavior of other components in the system.
	Mixer Valve	Type 649	Simulates a three-way mixing valve that combines two inlet fluid streams into one outlet stream. The mixing ratio is typically controlled by an external signal, allowing dynamic mixing based on temperature or flow rate requirements.
	Diverter Valve	Type 647	Simulates a three-way flow diverter valve. It takes a single inlet stream and splits it into

		two outlet streams, with the split ratio controlled dynamically by a control signal.
Pipe	Type 31	Type 31 simulates the thermal and hydraulic behavior of a pipe. It accounts for heat loss or gains to the surroundings, fluid flow characteristics, and time delays due to pipe length and flow rate
Equation Block		The equation block allows users to define custom mathematical expressions or logic within the TRNSYS environment. It is used to perform calculations, define control logic, manipulate inputs and outputs, or calculate intermediate values.

To ensure accurate distribution of cooling within the buildings, the air handling units (AHUs) were integrated with the Type 56 (Multizone Building Model) to represent the thermal zones of the buildings, allowing for dynamic heat transfer calculations. Type 760 was used (Air Handling Units) to model the AHUs that condition and distribute air within each thermal zone, considering fan power, cooling coil performance, and air mixing dynamics. The Tables below is the design parameters of the simulation of the building model and various components used for the simulation of the chilled water system.

Table 3:3. Model parameters of the cooling towers

SN	Parameters	Value	unit
1	inlet Fluid Temperature at Design	30.0	°C
2	Outlet Fluid Temperature at Design	24.0	°C
3	Fluid Flow Rate at Design	130823.3	kg/hr
4	Air Flow Rate at Design	243862	kg/hr
5	Fan Power at Design	19799.9	kJ/hr

Table 3:4. Model parameters of the chiller

SN	Parameters	Value	unit
1	Rated Capacity	651416.4	kJ/hr
2	Rated C.O. P	30.0	-
3	Number of CW Points	6	-
4	Number of CHW Points	6	-
5	CHW Set Point Temperature	7	°C

Table 3:5. Model parameters of the cooling water pump

SN	Parameters	Value	unit
1	Rated flow rate	218035	kJ/hr
2	Rated power	107325	kJ/hr
3	Number of power coefficients	1	-
4	Power coefficient	1	-

Table 3:6. Model parameters of the chilled water pump

SN	Parameters	Value	unit
1	Rated flow rate	218035	kJ/hr
2	Rated power	134228	kJ/hr
3	Number of power coefficients	1	-
4	Power coefficient	1	-

3.6 Development of predictive-adaptive chilled water flow control strategy

Each zone, located within different blocks of the building, has a unique thermal capacitance, which is pre-determined from the detailed energy models developed using the TRNSYS 3D plugin in SketchUp and exported to the simulation studio in TRNSYS. For control, every hour, temperature sensors in each zone send real time temperature readings to a central microcontroller (MC). The microcontroller uses these readings, along with the thermal capacitance of each zone, to accurately estimate the individual cooling load required to bring each zone to the desired setpoint of 24°C which is within the comfort temperature for cooling, assuming chilled water supply temperature of 7°C.

From this, the required chilled water flow rate for each zone is calculated. The microcontroller then sums the total flow demand from all zones to determine the overall flow rate that needs to be delivered. A control signal is generated to modulate the chilled water pump, ensuring it produces only the total required flow, thereby optimizing energy use and avoiding overcooling.

Once the total flow is established, the microcontroller also calculates the correct proportion of flow needed for each individual zone. Using this information, it sends signals to a network of diverting valves, adjusting each one to ensure that the right volume of chilled water is directed

to each zone. This coordinated actuation of valves ensures that every zone receives precisely the cooling it requires, maintaining consistent comfort across the building while maximizing the system's overall efficiency. Figure 3.16 is a flow chart for how the required flow rate of each zone is estimated through alterative process. The total flow rate required by the pump is now the summation of all the flow rate of each zone.

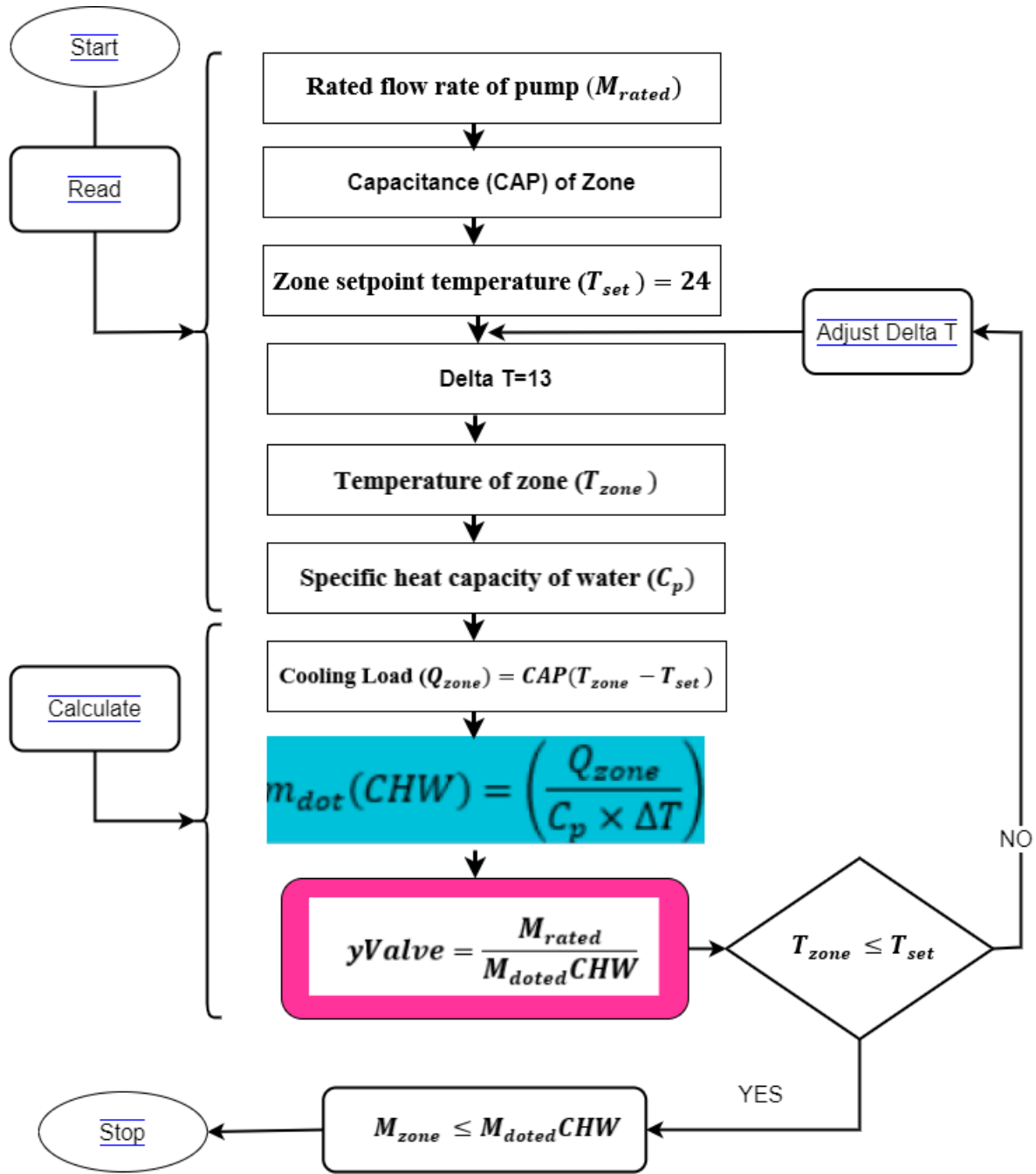


Figure 3.16. Flow chart illustrating the adaptive chilled water flow control strategy

3.7 Performance Simulation and Evaluation

Following the development of the thermal model of the case study buildings and the complete integration of the HVAC and chilled water plant system within the TRNSYS simulation environment, the performance of the system was evaluated under two distinct control

strategies: the existing constant flow control strategy and the newly developed adaptive flow control mechanism. This dual-mode simulation approach was adopted to enable comparative performance analysis, allowing for the quantification of improvements in operational efficiency and thermal comfort.

Simulations were executed over a one-year period using typical meteorological year (TMY) weather data for the site location to capture seasonal variations in environmental conditions. For each simulation run, hourly data were recorded for key system parameters including chilled water flow rates, zone temperatures, cooling energy consumption, pump energy usage, chiller load, and thermal comfort levels across the for the for the all the four blocks (A, B, C and D). These parameters collected and evaluated served as the basis for the quantification of the efficiency of the chilled water plant based on the two chilled water flow control strategy.

To capture representative thermal behavior across different weather conditions, the simulation is conducted using typical sunny and cloudy days derived from historical meteorological data. This approach helps evaluate the system's dynamic response under contrasting solar gain and ambient temperature conditions, which significantly influence space cooling loads and chilled water demand. By analyzing performance on these two distinct types of days, the system's adaptability, control responsiveness, and energy efficiency can be assessed across a broader operational envelope.

Key performance indicators (KPIs) such as cooling energy consumption, pumping energy consumption, thermal comfort compliance, system response time, chilled water utilization efficiency, and coefficient of performance (COP) are computed to assess system efficiency and occupant comfort. These metrics provide a quantitative basis for comparing different control strategies and identifying potential energy-saving opportunities. To quantitatively assess the

performance of the chilled water system under different control strategies, the equations of the next section were used to compute key performance indicators:

3.7.1 Chiller System Energy Consumption

This refers to the total energy consumed by the chillers (Chiller pump and Chiller fan) , the cooling tower pump and fan to meet the cooling demands of all thermal zones in each block. It serves as a primary metric for evaluating the overall energy efficiency of the chilled water plant system. It is found from equation (3.2):

$$E_{chiller} = \int_{t=1}^{t=stop} (\dot{E}_{chw_{pump}} + E_{chiller}) dt \quad (3.2)$$

$$E_{CT} = \int_{t=1}^{t=stop} (\dot{E}_{CT_{pump}}) dt \quad (3.3)$$

$$E_{consumption} = E_{chiller} + E_{CT} \quad (3.4)$$

Where

$E_{chiller}$ is the energy consumed by the chiller (kWh).

$\dot{E}_{CT}$ is the energy consumed by the cooling tower (kWh).

$\dot{E}_{chw_{pump}}$ is the energy consumed by the chilled water pump (kWh).

$E_{chiller}$ is the energy consumed by the chiller (kWh).

$\dot{E}_{CT_{pump}}$ is the energy consumed by the cooling tower pump (kWh) .

For this study, the energy consumption chiller will be evaluated based on the conventional constant flow control of the chilled water pump and the predictive adaptive flow control

strategy and the percentage difference of the performance will be evaluated relative to the baseline case.

3.7.2 Thermal comfort compliance

This metric reflects the percentage of time each thermal zone remains within the acceptable temperature range of 22–26°C, based on indoor thermal comfort standards such as ASHRAE 55. Higher compliance indicates better control over indoor environmental quality. Estimated from equation below.

$$TCC = \left(\frac{T_{compliant}}{T_{total}} \right) \times 100 \quad (3.5)$$

Where TCC is the thermal comfort compliant, $T_{compliant}$ is number of time steps where zone temperature is within comfort range and T_{total} is the total number of time steps evaluated. For this study, the zone temperature compliance of two selected zones in each of the four blocks will be compared based on the two cooling operations of the HVAC system (i.e. constant chilled water flow and predictive- adaptive flow control).

3.7.3 Coefficient of Performance (COP)

The COP of the chiller system is calculated as the ratio of cooling load met to electrical energy consumed. It provides insight into the efficiency of the entire cooling process and the impact of flow modulation on chiller performance. The annual COP of the chilled water plant was evaluated for the four blocks based on the two chilled water flow control strategies. For the base case scenario, the COP is evaluated from equations (3.6) and (3.7) :

$$COP_{base} = \int_{t=1}^{t=stop} \left(\frac{\dot{Q}_{cbase}}{\dot{p}_{chiller_{base}}} \right) dt \quad (3.6)$$

$$COP_{control} = \int_{t=1}^{t=stop} \left(\frac{\dot{Q}_{ccontrol}}{\dot{p}_{chiller_{control}}} \right) dt \quad (3.7)$$

Where COP_{base} is the COP evaluated based on the constant chilled water flow, $COP_{control}$ is the COP evaluated based on the controlled chilled water flow rate, $\dot{p}_{chiller_{base}}$ (kWh) is the electrical power input to the chiller based on the constant flow control of the chilled water,

$\dot{p}_{chiller_{control}}$ (kWh) is the electrical power input to the chiller based on the controlled flow rate of the chilled water, $\dot{Q}_{cbase}$ (kWh) is the cooling load met by the chiller based on the constant flow control of the chilled water and, $\dot{Q}_{ccotrol}$ (kWh) is the cooling load met chiller based on the controlled flow control of the chilled water. The COP is calculated based on the annual performance of the system.

3.7.4 Chilled Water Utilization Efficiency

This quantifies how effectively the chilled water flow is distributed and utilised in each building. In this study, the chilled water utilization efficiency is calculated per zone and then per building and comparison is made for the case of constant flow and controlled of the chilled water. This parameter is defined as the ratio of actual cooling met in each zone to the total chilled water energy supplied to the zone as expressed in equation (3.8).

$$\eta_{CHW} = \int \frac{\dot{Q}_{zone,i}}{\dot{Q}_{CHW,total}} \quad (3.8)$$

Where η_{CHW} is the chilled water utilization efficiency, $\dot{Q}_{zone,i}$ is the cooling energy received by zone, and $\dot{Q}_{CHW,total}$ is the total chilled water energy supplied by the plant. The comparative simulation results of the baseline (constant flow) and the adaptive control analysed and compared.

3.7.5 Carbon Footprint Reduction

Carbon footprint reduction (CFR) represents the amount of CO₂ emissions avoided by using the chilled water plant in meeting the building plant operated based on the predictive -adaptive flow control relative to the constant flow control of the same chilled water. It is computed as:

$$CFR = E_{\text{offset}} \times EF_{\text{grid}} \quad (3.11)$$

Where:

E_{offset} = Total energy offset by proposed chilled water flow control [kWh].

EF_{grid} = Emission factor of the grid electricity [kg CO₂/kWh].

A typical emission factor for grid electricity is approximately 0.6 kg CO₂/kWh [122].

Chapter 4: Results and Discussion

4.1 Introduction

This section presents the comprehensive evaluation of the performance of two control strategies; Predictive-Adaptive Flow Control (PAFC) and Constant Flow (CF) for operating the chilled water-cooling system in a in meeting the cooling load of the case study building (Block B of the university of Nottingham Malaysia) located in Kuala Lumpur. The analysis focuses on the system's response to varying weather conditions, particularly comparing sunny and cloudy days. Further, the section evaluates the hydraulic implications, pump and chiller power consumption, temperature differential across the chiller, and the resultant carbon footprint under each control strategy.

4.2 Validation of formulated model

The simulation model's performance was evaluated by comparing the predicted power consumption of both the chiller and pump against experimental measurements across a flow rate range of 2.0 to 5.0 m³/h. The model's simulated chiller power closely follows the experimental data, with the coefficient of determination (R^2) calculated at approximately 0.97 as seen from Figure 4.1. This high R^2 value indicates that the model explains 97% of the variance observed in the experimental chiller power, demonstrating excellent predictive capability.

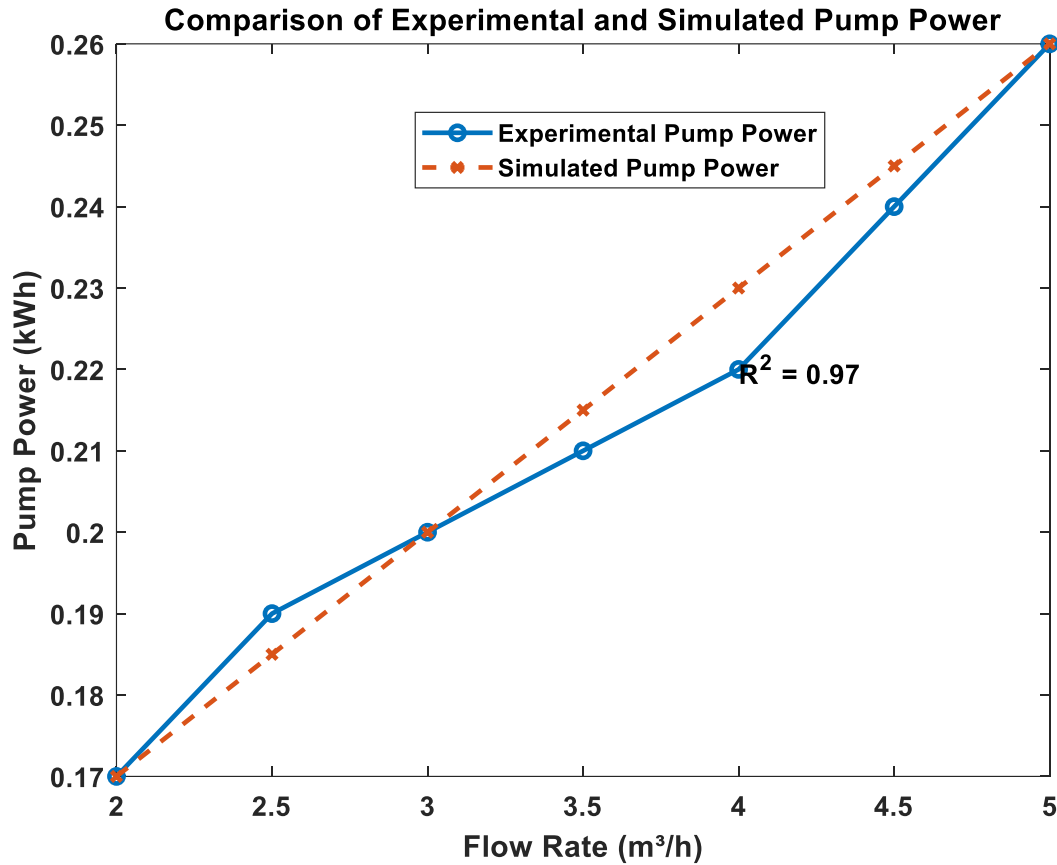


Figure 4.1. Comparison of simulated pump power performance with the experimental performance

Such a strong correlation suggests that the model accurately captures the key physical and operational dynamics governing chiller power consumption across the tested flow rates. This level of agreement supports the model's use in performance analysis, energy forecasting, and system optimization for chiller systems.

Similarly, the simulated pump power exhibited near-perfect agreement with experimental values, yielding an R^2 of approximately 0.87 as seen in Figure 4.2. This result confirms the model's ability to accurately represent pump operation, reflecting the primarily linear relationship between flow rate and pump power consumption within the tested range.

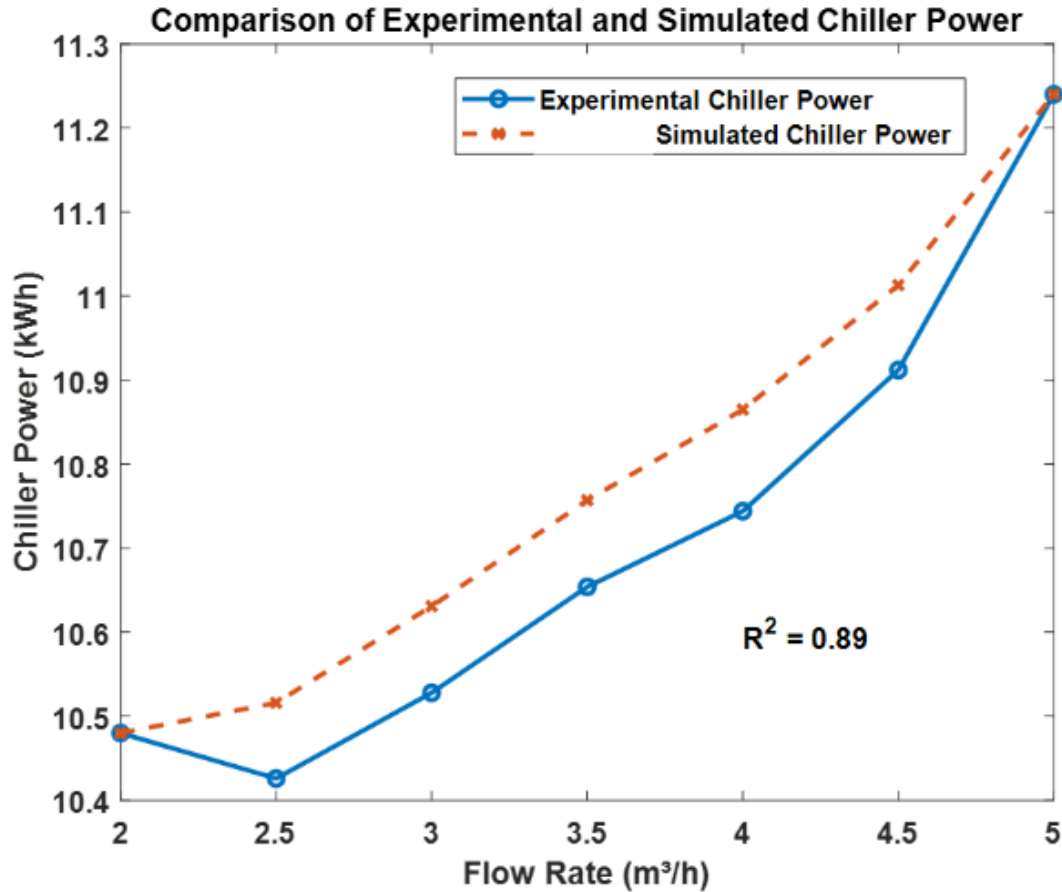


Figure 4.2. Comparison of simulated chiller power performance with experimental performance

The high fidelity of the pump simulation indicates that the underlying assumptions about pump efficiency, hydraulics, and motor characteristics are well-founded, allowing confident use of the model for design, control, and optimization purposes.

The combined results demonstrate that the simulation model provides a robust representation of the chiller-pump system's power consumption. With R^2 values exceeding 0.8 for both components, the model meets rigorous validation standards, confirming its utility for both academic research and practical engineering applications.

The strong predictive performance facilitates accurate energy consumption estimation, enabling improved system design and operational decision-making. Further refinement could focus on expanding the model's scope to transient conditions or integrating additional physical phenomena, but the current results establish a solid foundation for ongoing work.

4.3 Building thermal performance

4.3.1 Weather characteristic and thermal dynamic behaviour of building

To evaluate the effectiveness of the formulated control strategies for operating the chilled water-cooling system in reliably meeting the building's cooling demand, it is essential to assess their performance under contrasting weather conditions specifically, a typical sunny day and a typical cloudy day. This approach is justified by the significant influence of weather parameters, particularly solar irradiance and relative humidity, which are primary drivers of cooling load in buildings.

Figure 4.3 shows the variation in solar irradiance observed in Kuala Lumpur under representative sunny and cloudy day conditions. Subsequently, Figure 4.4 illustrates the simulated dynamic indoor temperature profiles of the case study building for these two weather scenarios, providing insight into the thermal response of the building under varying solar and atmospheric conditions.

It is seen from the Figures 4.3 that on a sunny day, solar irradiance values rise sharply from as early as 7 AM, peaking between 11 AM and 2 PM at over 960 W/m². This intense and sustained solar gain could lead to a significant heat load on the building envelope, as evident from the zone temperatures climbing as high as 33.0°C by 4 PM as seen in Figure 4.4. Throughout the solar-active period (7 AM to 4 PM), zone temperatures consistently remain above 31°C, indicating a substantial deviation from the desired setpoint of 24°C. This deviation represents a high cooling demand, as the building would require a significant amount of thermal energy

removal to maintain the setpoint temperature of 24°C. The values and duration of the zone's temperature suggest that on sunny days, the cooling system must operate for longer periods and at higher capacity to ensure thermal comfort. Additionally, the lag in temperature rise, with peak indoor conditions occurring after peaking solar irradiance, reflects heat retention within the building, further increasing the load on the cooling system in the late afternoon hours.

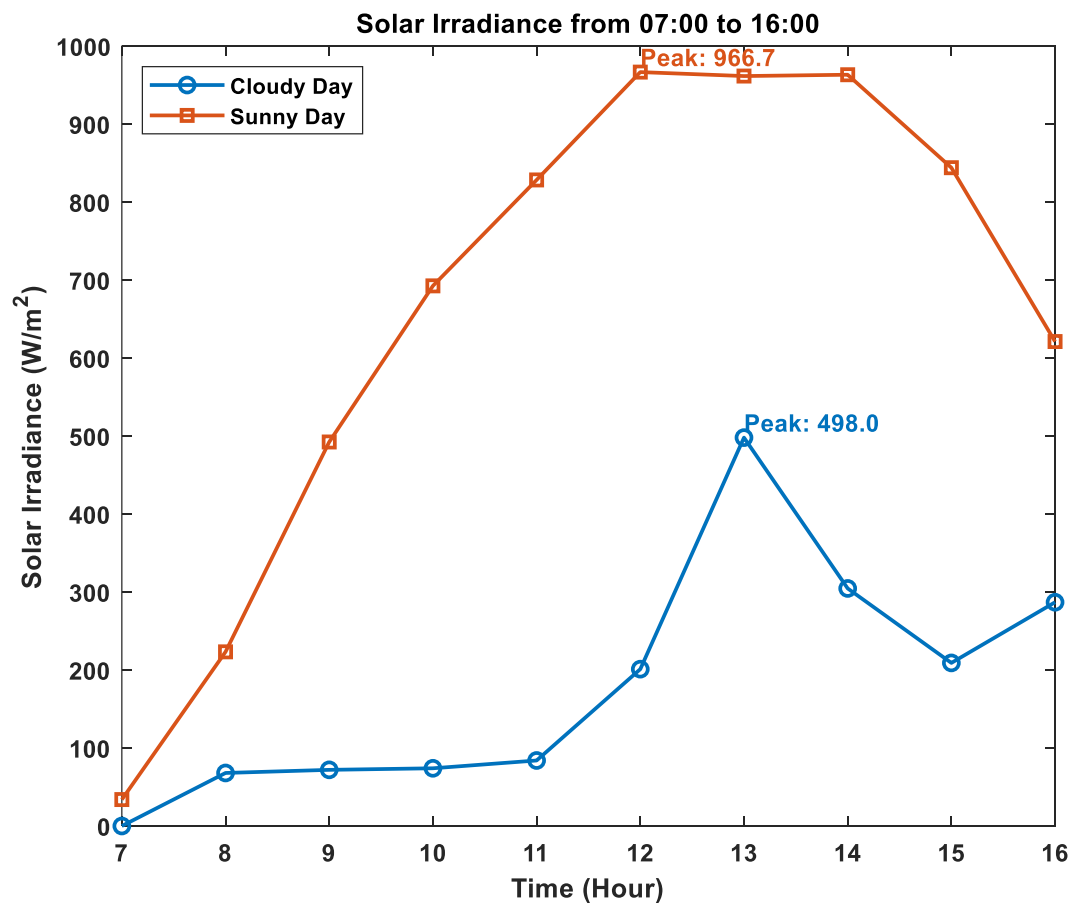


Figure 4.3. Irradiance characteristics of Kuala Lumpur on typical cloudy (28/01/25) and sunny days (31/03/25)

In contrast, on a cloudy day, the solar irradiance is much lower and less consistent, with a peak of just 498 W/m^2 around 1 PM. As a result, the indoor temperature profile remains relatively lower, peaking at only 31.5°C. The smaller temperature deviation from the setpoint (typically between 6°C and 7.5°C) implies a significantly lower cooling demand.

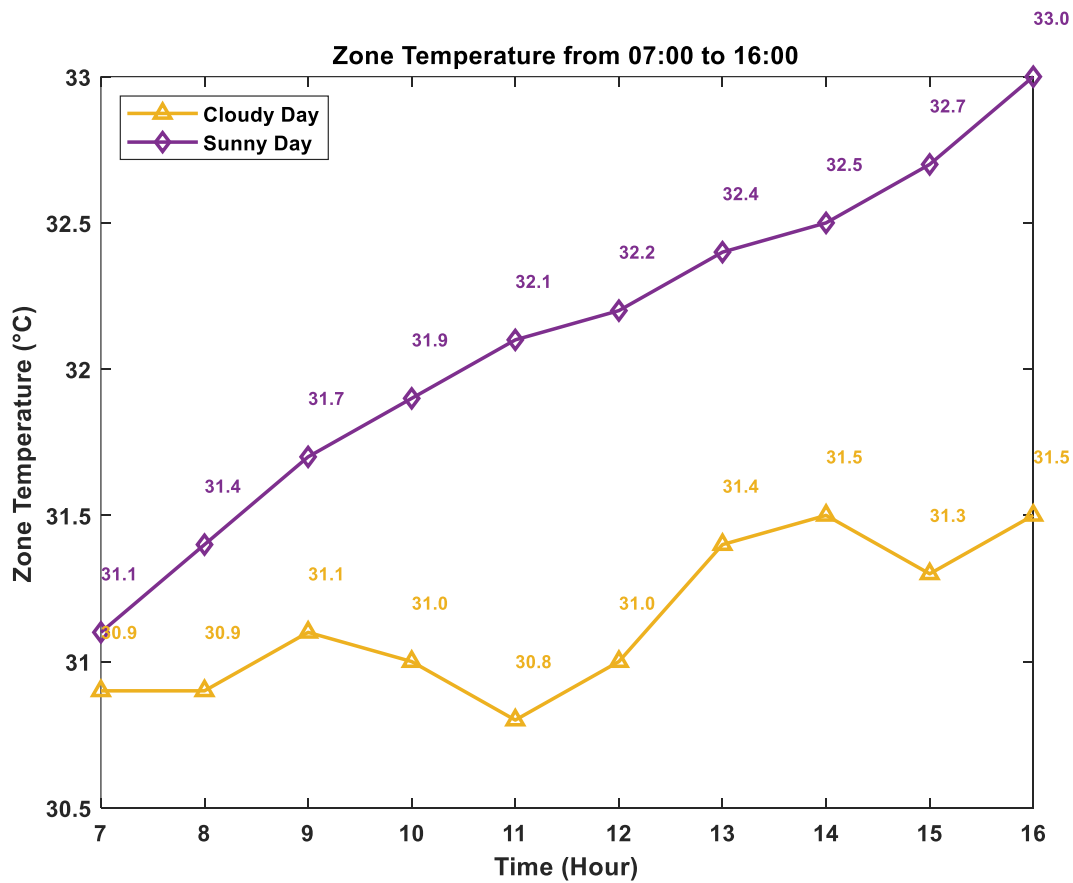


Figure 4.4. Average simulated building indoor temperature on typical cloudy and sunny days

Comparing the two scenarios, it is clear that cooling demand on sunny days is expected to be higher due to more intense and sustained solar gains. This has direct implications for energy consumption, system sizing, and occupant comfort. HVAC systems must be designed to accommodate peak cooling loads driven by sunny conditions, which are likely to represent worst-case scenarios in thermal performance assessments.

Notably, from Figure 4.4 it is clear that sunny days impose a significantly greater cooling load than cloudy days, driven primarily by higher solar irradiance and resultant internal temperature elevations.

4.3.2 Average controlled building temperature under the strategies

Figures 4.5 and 4.6 present the average controlled indoor temperature of the building on typical cloudy and sunny days, respectively, in response to the operation of the chilled water-cooling system based on the predictive and constant flow strategies. These Figures shows the building thermal characteristic of the building under the two control strategies governing the operation of the chilled water pump. The comparison highlights the effectiveness of each control approach in maintaining indoor thermal comfort under varying weather conditions.

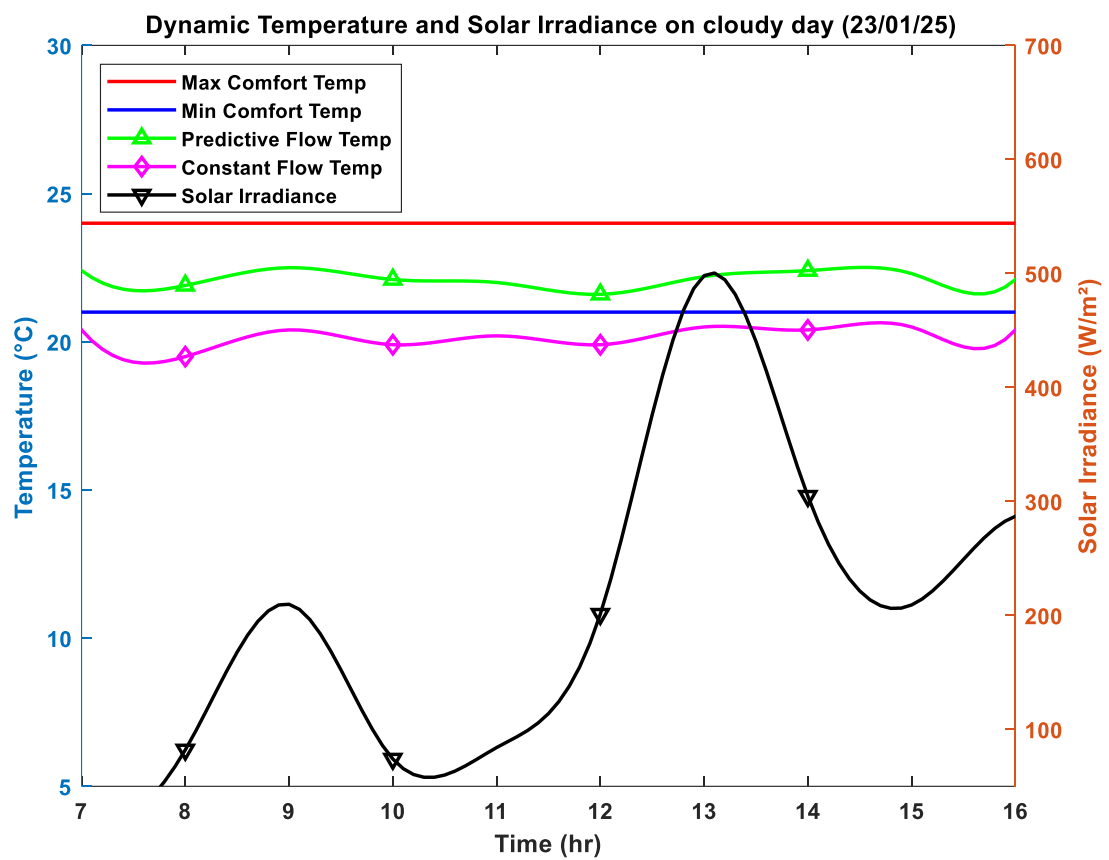


Figure 4.5 Building temperature under the predictive and constant flow control strategies on typical cloudy day

Figure 4.5 shows the dynamic temperature characteristics of a building on a typical cloudy day (23/01/25), comparing the average indoor temperatures based on a chiller plant employing two the predictive-adaptive flow control and constant flow control.

It is evident from Figure 4.5 that when employing the predictive-adaptive flow control, the average building temperature is effectively reduced and maintained within or slightly below the minimum comfort temperature during occupied hours (7:00 to 16:00 hours). As seen, from 7:00 to 16:00 hours, temperatures range between approximately 21.6°C and 22.5°C, comfortably within the comfort band of 21°C to 24°C. This suggests that the predictive-adaptive control strategy effectively anticipates thermal loads and dynamically adjusts chilled water flow rates to optimize cooling performance, thereby improving thermal comfort and likely enhancing energy efficiency by avoiding unnecessary cooling.

In contrast, the constant chilled water flow control strategy as seen in Figure 4.5 results in slightly lower average temperatures compared to the predictive control, ranging approximately between 19.5°C and 20.5°C during the same daytime period. While this indicates a more aggressive cooling effect, the temperatures are generally below the minimum comfort temperature of 21°C, which may lead to overcooling and occupant discomfort. This also suggests potential energy inefficiencies, as constant flow strategy does not adjust to real-time thermal loads, leading to continuous cooling regardless of actual demand.

Comparatively, the predictive-adaptive flow control demonstrates a better balance between maintaining thermal comfort and avoiding overcooling. By modulating chilled water flow in response to forecasted thermal conditions, this approach potentially reduces energy consumption while maintaining temperatures within a desirable comfort range.

Overall, it indicates that predictive-adaptive flow control offers superior control of indoor temperatures, maintaining comfort while potentially optimizing energy use. In contrast, constant flow control, although simpler, may lead to excessive cooling and higher operational costs.

Similarly, Figure 4.6 presents the average indoor temperature dynamics of a building on a typical sunny day (31/03/25). Again, the predictive-adaptive flow control strategy effectively moderates indoor temperatures throughout the day, maintaining values mostly within the thermal comfort range of 21°C to 24°C. During peak solar irradiance hours (7:00 to 16:00), temperatures remain between 20.8°C and 22.9°C, demonstrating the system's capability to anticipate cooling loads and dynamically adjust chilled water flow rates accordingly.

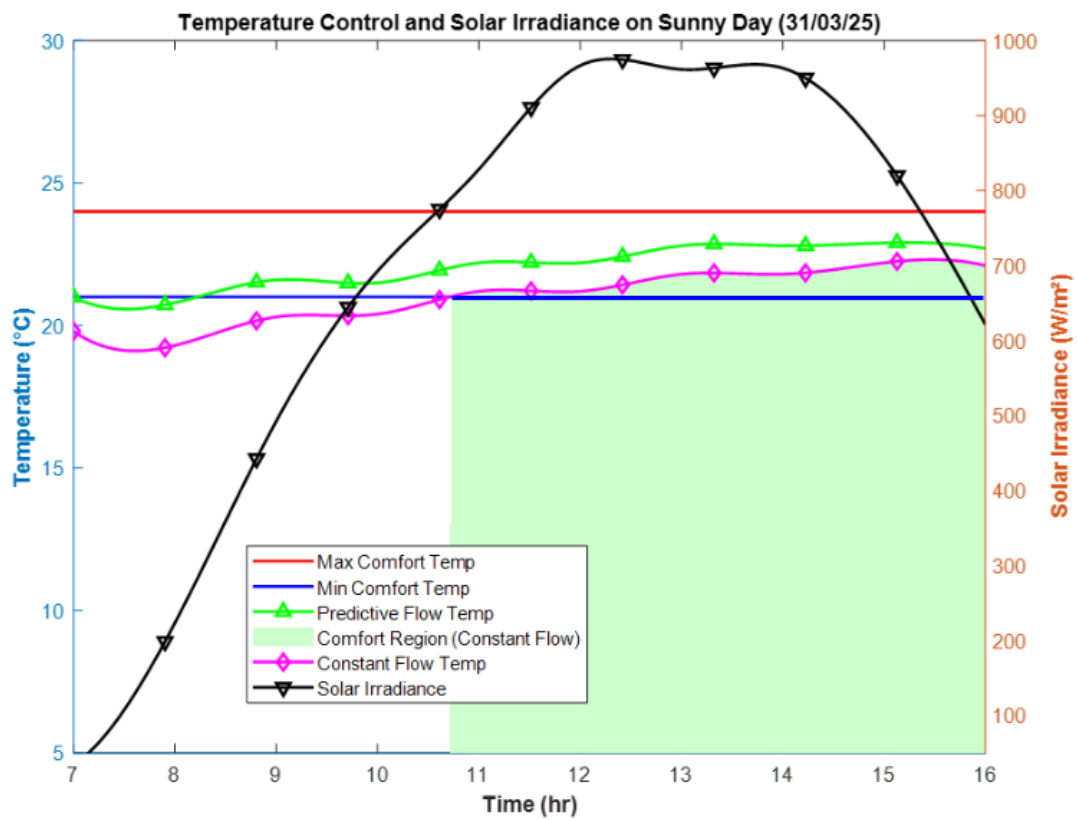


Figure 4.6. Building temperature under the predictive and constant flow control strategies on typical sunny day. The constant flow control strategy results in lower indoor temperatures compared to the predictive strategy, generally ranging from 19.3°C to 22.2°C during daylight hours. While this achieves a reduction in peak temperatures, the frequent occurrence of temperatures below the minimum comfort threshold of 21°C suggests a tendency toward overcooling. This non-adaptive approach continuously delivers chilled water at a fixed rate regardless of the real-time

cooling demand, which may lead to increased energy usage and discomfort due to excessive cooling.

Comparison of indoor temperature under constant flow (magenta) and predictive flow (green) control strategies relative to the comfort region (light green). The comfort region, defined by the minimum (blue) and maximum (red) acceptable temperatures, indicates the desired indoor thermal conditions. The predictive flow strategy maintains temperatures consistently within the comfort zone, while constant flow shows minor deviations near the lower boundary. Solar irradiance (black) impact on indoor temperature is also shown.

Overall, the data indicate that the predictive-adaptive flow control offers a more balanced and responsive cooling strategy on a sunny day, successfully maintaining indoor temperatures within acceptable comfort limits while avoiding unnecessary energy expenditure. In contrast, the constant flow strategy, while effective at lowering peak temperatures, may compromise occupant comfort due to overcooling and is likely less energy efficient.

4.3.3 Indoor Temperature Compliance Analysis

Figure 4.7 reveals the monthly indoor temperature compliance of the case study building cooled based on the predictive-adaptive chilled water pump control strategy of the chilled water-cooling plant. Figure 4.7 shows the number of hours during which the average zone temperature remains within the comfort band of 22°C to 24°C refers to as “compliance”, and the durations when temperatures fall below the minimum comfort temperature of 21°C.

Monthly analysis reveals that most months achieve over 80% compliance with the comfort range, with the highest compliance observed in May (289 hours within comfort out of 310 scheduled hours, approximately 93%). Months such as January and March also demonstrate strong compliance exceeding 80%. Slightly lower compliance rates are evident in months like

February and September, primarily due to increased occurrences of temperatures falling below the minimum comfort threshold of 22°C.

For a scheduled cooling operation between 7.00 to 16.00 hour, it is estimated that the cooling schedule is 3650 hours per year. Under the predictive flow control operation of the chiller plant, the building's indoor temperature was maintained within the prescribed comfort range for approximately 3118 hours, representing an impressive compliance rate of roughly 85%. This high level of compliance underscores the effectiveness of the predictive-adaptive control strategy in maintaining occupant thermal comfort throughout varying climatic conditions.

Instances where indoor temperatures fall below 22°C are relatively limited, totalling 524 hours annually (about 14% of scheduled cooling hours). These undercooling events are more prevalent during cooler months, such as January, February, and September, indicating a potential for slight over-conditioning during these periods. Conversely, overheating beyond 24°C is notably rare, with only 8 hours recorded annually, predominantly in December. This suggests that the predictive control strategy effectively prevents excessive indoor heat accumulation and manages cooling loads efficiently to minimize thermal discomfort from overheating.

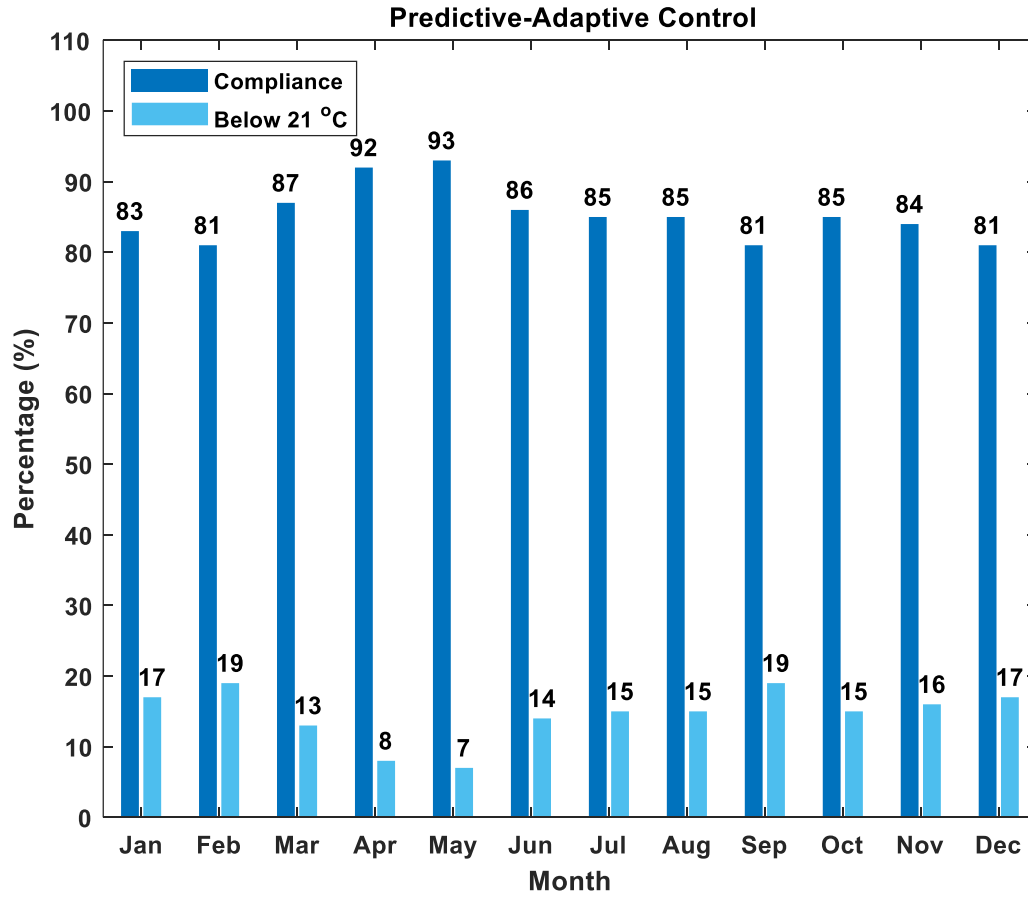


Figure 4.7. Monthly indoor temperature compliance analysis based on predictive-adaptive control in 2024

The dominance of compliance hours within the comfort range implies that the predictive-adaptive control not only enhances occupant comfort but likely optimizes energy consumption by avoiding unnecessary overcooling or overheating. The limited undercooling events, while warranting attention, may be mitigated through further tuning of control parameters to avoid excessive cooling in cooler months without compromising comfort during warmer periods.

Similarly, Figure 4.8 shows the assessment of indoor temperature compliance for a building cooled by a constant chilled water pump control strategy. Over the annual total of 3650 scheduled cooling hours, the building maintains indoor temperatures within the prescribed comfort range for only 779 hours, corresponding to approximately 21% compliance. This low

level of compliance indicates a significant shortfall in the system's ability to sustain occupant comfort throughout the year when using constant flow control.

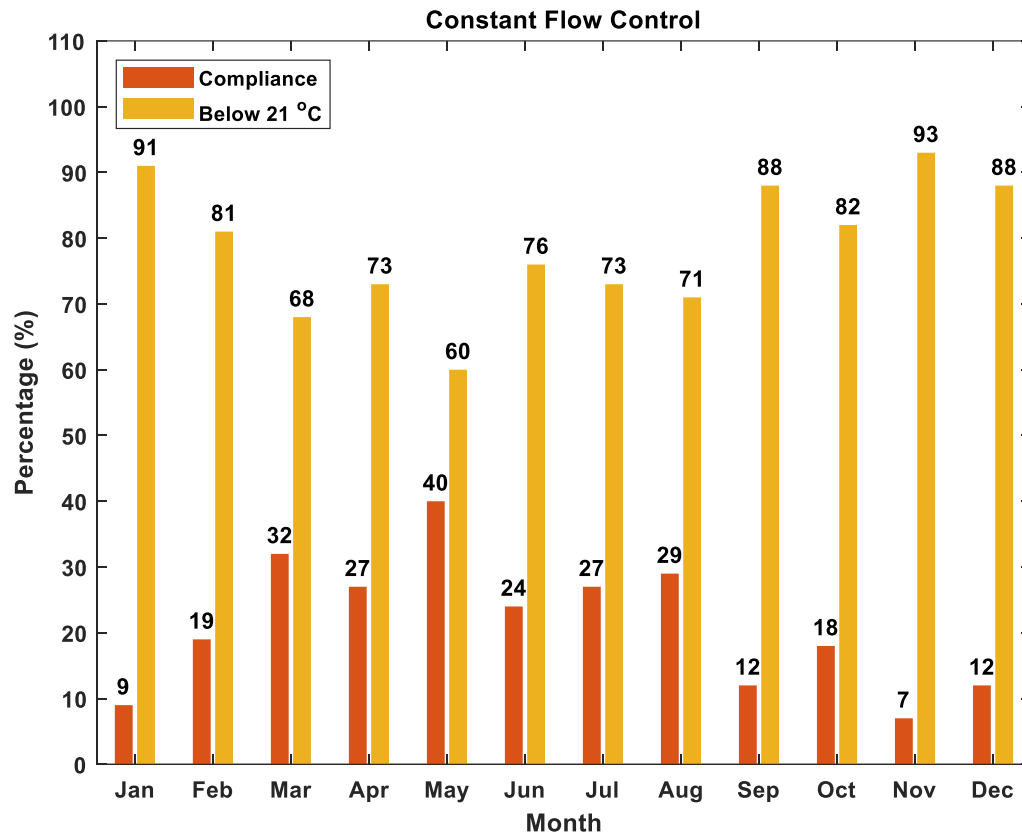


Figure 4.8. Monthly indoor temperature compliance analysis based on constant flow control

The Figure reveal that a significant majority of cooling hours of 2871 hours or about 79% of the total are characterized by average zone temperatures falling below 22°C. This widespread undercooling is consistent across all months, with minimal variation, and is particularly pronounced in months such as January and November, where compliance hours within the comfort band are as low as 9% and 7% respectively. Importantly, there are no recorded instances of zones temperature going above 24°C, indicating that the system consistently cools below the comfort range but never allows temperatures to exceed the upper comfort threshold.

The predominance of zones temperatures below 22°C suggests that the constant chilled water flow control strategy is overly aggressive, leading to frequent overcooling. This can result in occupant discomfort due to cold indoor conditions and likely implies excessive energy consumption, as the cooling system operates continuously at a fixed flow rate regardless of actual cooling demand. Compared to the predictive-adaptive control strategy, which maintained approximately 85% compliance with the comfort range (as shown in Figure 4.6), the constant flow control strategy performs substantially worse in preserving thermal comfort.

4.4 System dynamics and energy analysis

4.4.1 Flow Rate Dynamics and Hydraulic Implications

A fundamental aspect of chilled water system performance is the modulation of flow rate to match cooling load demands. Figure 4.9 illustrates the flow rate profiles on a typical cloudy day, where the constant flow (CF) strategy maintains a constant flow rate fixed at approximately 85,425.6 kg/hr over the operational hours from 07:00 to 16:00. This fixed-flow approach disregards the diurnal variation in building cooling demand, resulting in continuous circulation of chilled water even during low-load periods. By contrast, Predictive Adaptive flow control (PAFC) dynamically adjusts flow rates based on predictive algorithms and real-time load feedback, modulating flow between roughly 24,247.3 kg/hr in early hours and 43,958.2 kg/hr during peak demand. This adaptive control leads to an average flow reduction of approximately 47% compared to CF, emphasizing the inefficiency inherent in constant high flow operation during subdued load conditions.

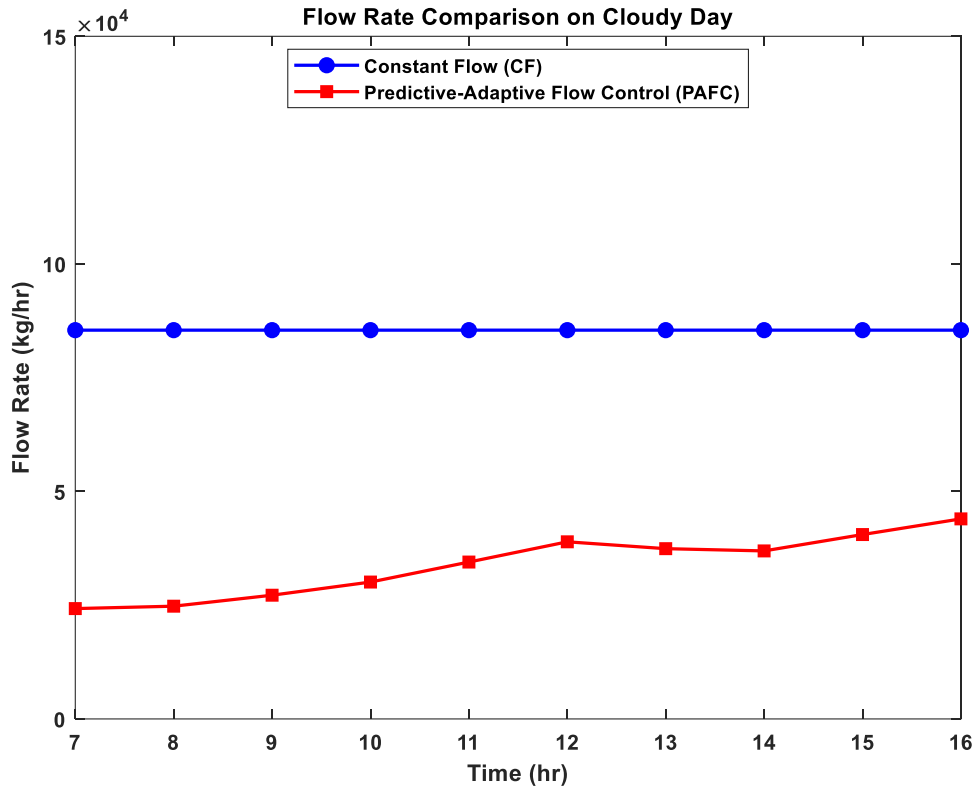


Figure 4.9. Comparison of the system flow rate under the two strategies on typical cloudy day

This disparity becomes more pronounced when considering the typical sunny day scenario depicted in Figure 4.10. Here, the CF system again delivers a constant high flow rate of about 85,425.6 kg/hr, while PAFC adjusts flow from 35,193 kg/hr in the early morning, ramping to 74,124 kg/hr by late afternoon as cooling demand intensifies. The adaptive strategy reduces the average flow by 20–60% during low to moderate load periods, reflecting a more responsive and load-congruent system operation.

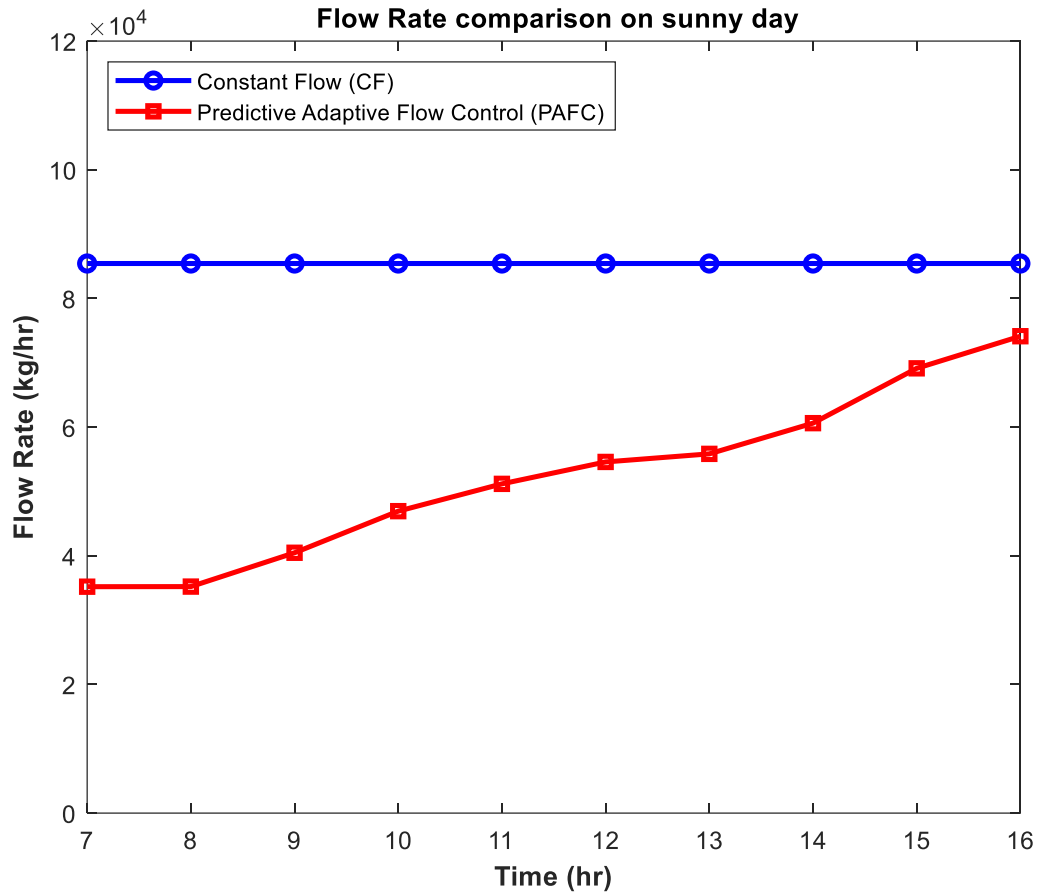


Figure 4.10 .Comparison of the system flow rate under the two strategies on typical sunny day

The hydraulic implications of these flow dynamics are significant. Excessive flow rates under CF contribute to increased friction losses within piping and valves, necessitating higher pump power and accelerating mechanical wear. In contrast, PAFC's tailored flow reduction reduces these losses and associated energy consumption, simultaneously mitigating wear and extending component lifespan. Furthermore, the ability to operate at lower flow rates under PAFC offers opportunities for infrastructure optimization, including the potential for downsizing piping and pump capacities, thus reducing both capital and maintenance costs.

4.4.2 Dynamic Pump Power Consumption and Energy Efficiency

Closely linked to flow dynamics is the energy consumed by pumps to circulate chilled water. Figure 4.11 demonstrates that on a cloudy day, CF operation maintains a steady pump power

consumption of approximately 10.62 kWh per hour, reflecting the constant hydraulic load imposed by the fixed flow rate. Conversely, PAFC's pump power varies between 3.0 kWh and 5.5 kWh, mirroring its flow adjustments. This adaptive operation yields a substantial average pump power reduction of approximately 60% relative to CF, evidencing the energy savings that can be realized by avoiding over-pumping during periods of lower cooling demand.

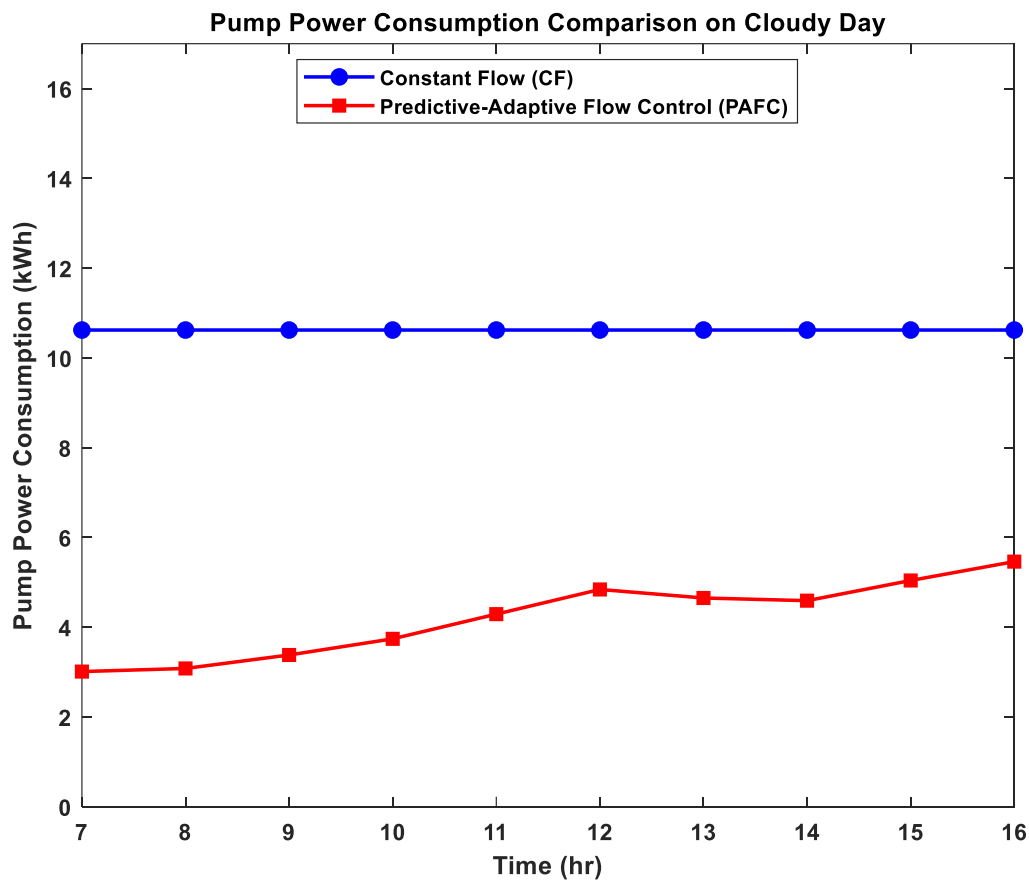


Figure 4.11. Comparison of the pump power consumption under the two strategies on typical cloudy day

This trend persists under sunny day conditions (Figure 4.12), where CF pump power remains constant at around 10.6 kWh, and PAFC power consumption varies from 4.4 kWh to 9.2 kWh. The variability corresponds closely to the fluctuating flow rates required to meet changing thermal loads, resulting in pump power savings between 13% and 59%. This significant

reduction in pump energy not only lowers operational electricity costs but also decreases thermal and mechanical stresses on motor bearings and pump components, which are critical for reliable long-term plant operation.

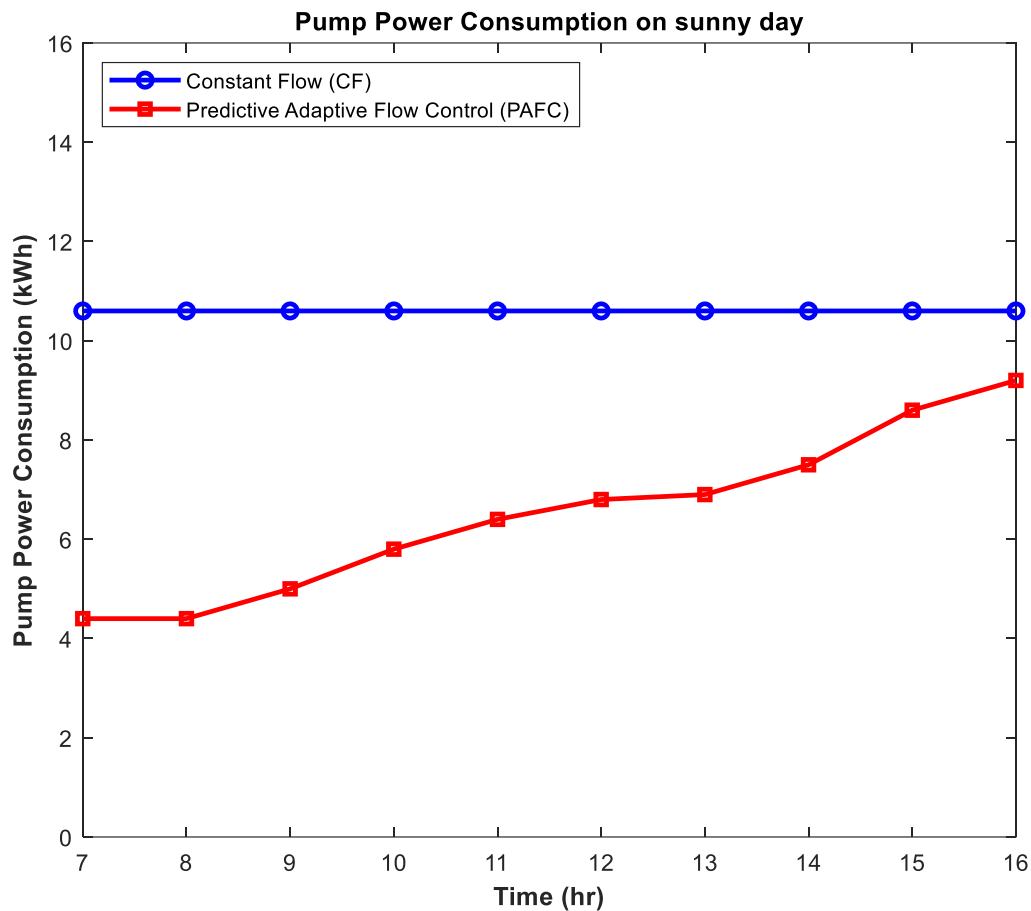


Figure 4.12. Comparison of the system pump power consumption under the two strategies on typical sunny day

The pump power profiles emphasize the limitations of CF systems, which expend unnecessary energy maintaining maximum flow regardless of load, versus the optimized, load-responsive operation enabled by PAFC. This is particularly valuable in commercial and industrial cooling contexts, where pumps often run continuously and energy savings accumulate significantly over time.

4.4.3 Chiller Power Consumption and Load Matching

Beyond pumping energy, the efficiency of the chiller itself in converting electrical input to cooling output is central to overall plant performance. Figure 4.13 shows chiller power consumption on a cloudy day, where CF systems consume between 287 kWh and 356 kWh per hour, whereas PAFC power consumption is markedly lower, ranging from 166 kWh to 291 kWh. This equates to an approximate 28% reduction in energy usage under PAFC. Such savings are attributable to PAFC's superior load matching capability: by adjusting chilled water flow according to actual cooling demand, the system prevents overcooling and minimizes chiller cycling, which are common inefficiencies under CF operation.

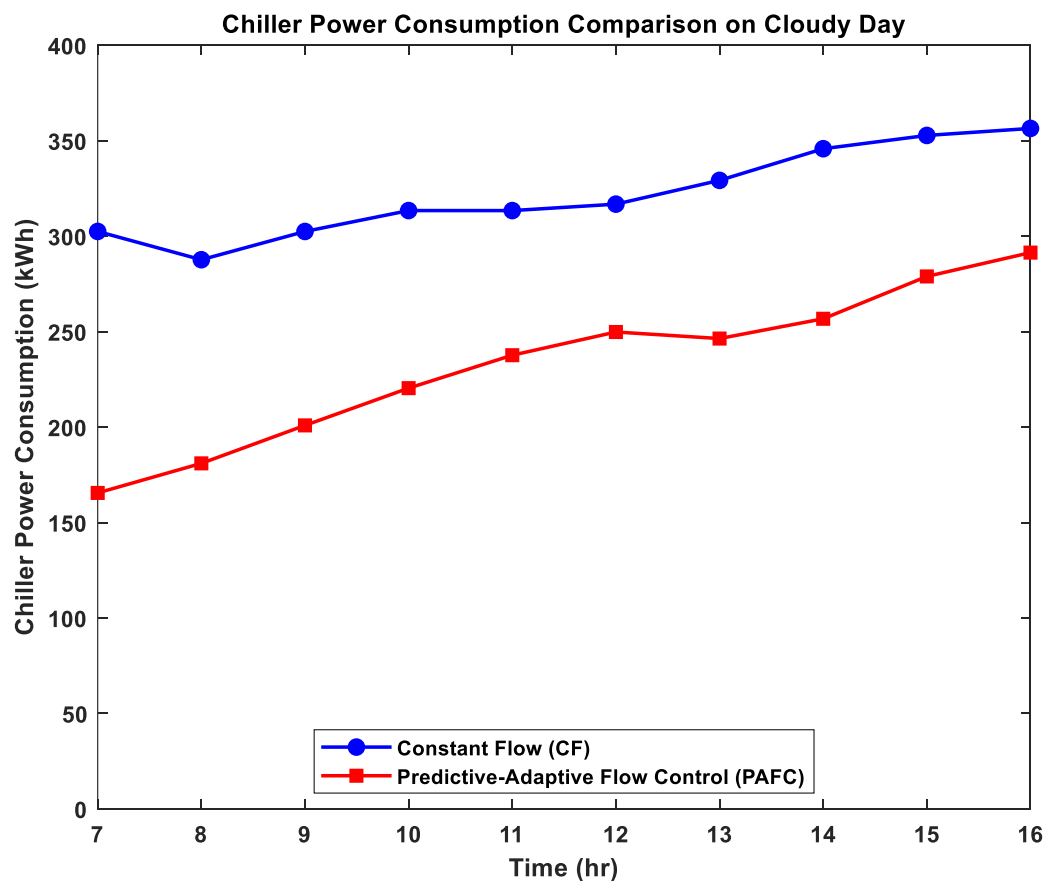


Figure 4.13. Comparison of the system chiller power consumption on typical cloudy day

Under sunny conditions (Figure 4.14), CF chiller power increases steadily from 268.3 kWh to 467.5 kWh, reflective of the fixed high flow and corresponding cooling demand. PAFC, however, consistently exhibits lower power consumption, ranging from 186.4 kWh to 449.5 kWh, with peak power reduced by approximately 4% and early-hour consumption decreased by more than 30%. This more precise alignment of cooling output with load requirements not only reduces electrical demand but also diminishes mechanical wear on critical compressor components, enhancing system reliability and reducing maintenance frequency.

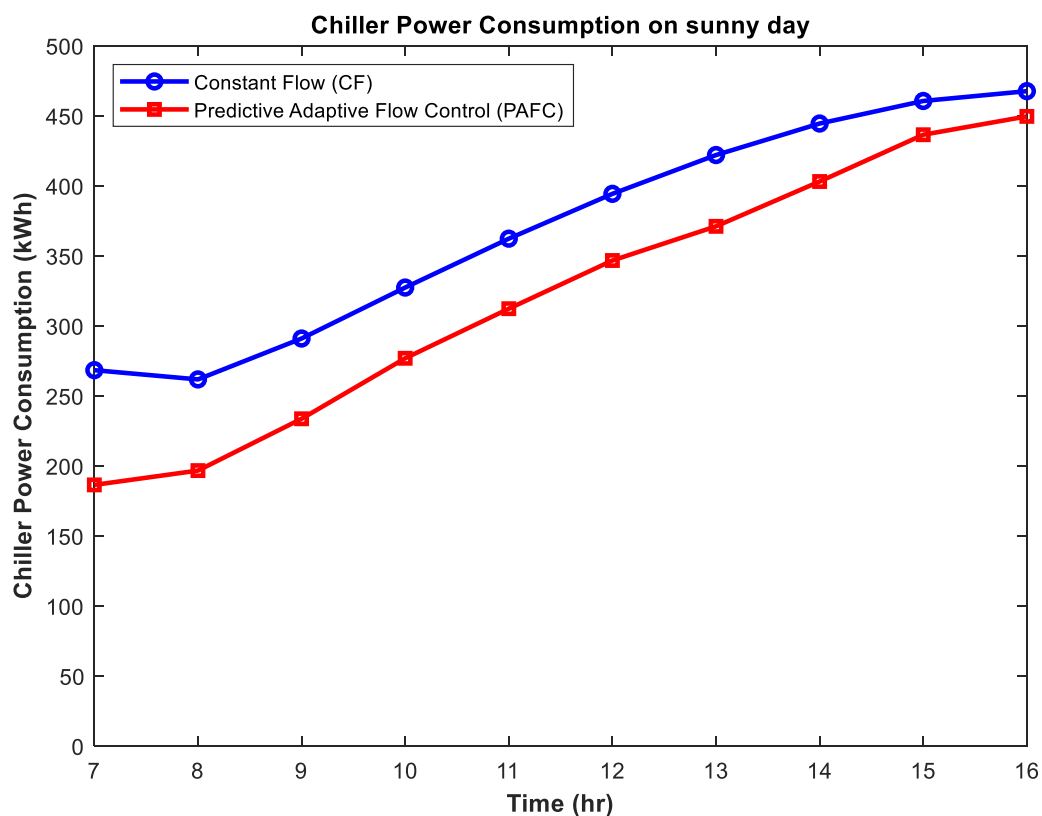


Figure 4.14.. Comparison of the system chiller power consumption on typical sunny day

This comparative analysis of chiller power reinforces the essential benefit of predictive and adaptive flow control: by avoiding the rigid flow conditions imposed by CF, PAFC improves

operational efficiency, leading to significant reductions in electrical consumption and extended equipment longevity.

Although the constant-flow strategy maintains a fixed chilled-water mass flow rate of the chilled water through the evaporator, the chiller's power consumption does not remain constant as seen in both Figure 4.13 and Figure 4.14. This variation is because several thermodynamic and operational factors continue to vary during real building operation. First, the cooling load imposed by the building fluctuates throughout the day due to changes in occupancy, internal heat gains, and outdoor environmental conditions. These variations directly affect the return-water temperature entering the evaporator. A higher return temperature increases the refrigeration load, requiring the compressor to perform more work, thereby increasing instantaneous power consumption.

Second, the entering condenser-water temperature (ECWT) or outdoor air temperature (in air-cooled chillers) varies with ambient conditions. An increase in ECWT elevates the condensing pressure and widens the compressor pressure lift. Since compressor work is strongly dependent on pressure differential across the refrigerant cycle, higher condensing pressures result in higher power draw even when evaporator flow is fixed.

4.4.4 Temperature Difference Across the Chiller and Thermal Effectiveness

A crucial indicator of thermal performance in chilled water systems is the temperature differential ΔT across the chiller. Figure 4.15 illustrates that on a cloudy day, PAFC achieves a ΔT ranging from 3.8°C to 6.6°C, which is approximately 65% higher than the 2.32°C to 3.65°C range observed under CF control. This elevated ΔT signifies that chilled water extracts more thermal energy per unit volume circulated, reflecting enhanced heat transfer efficiency. The implication of this higher ΔT is twofold: it enables the system to

meet cooling loads with lower volumetric flow rates and reduces frictional losses, further decreasing pumping energy consumption.

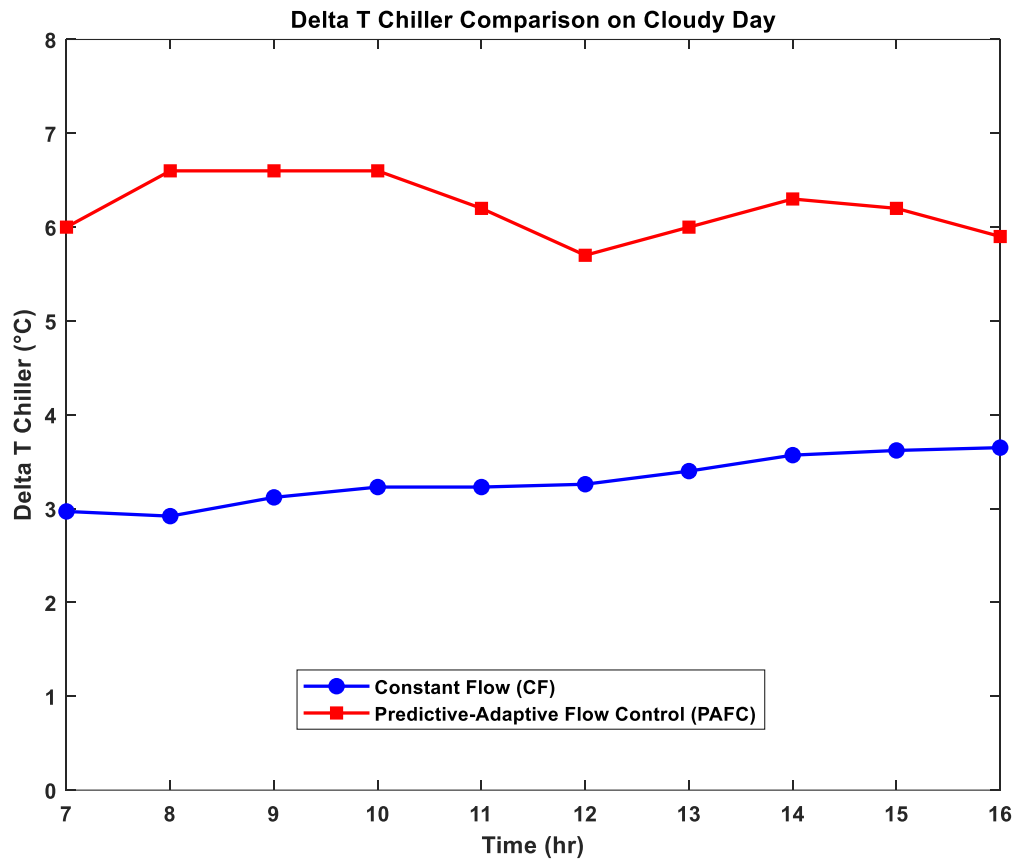


Figure 4.15. Comparison of the chiller Delta-T on typical cloudy day

The effect is even more pronounced on a sunny day (Figure 4.16), where PAFC attains delta-T values of around 4.62°C at 07:00 compared to only 2.64°C under CF an approximate 75% increase. This improvement arises from the longer residence time of water within the chiller's heat exchanger at reduced flow rates, which facilitates greater heat absorption. Conversely, CF's fixed high flow diminishes fluid residence time and impairs heat exchanger efficiency.

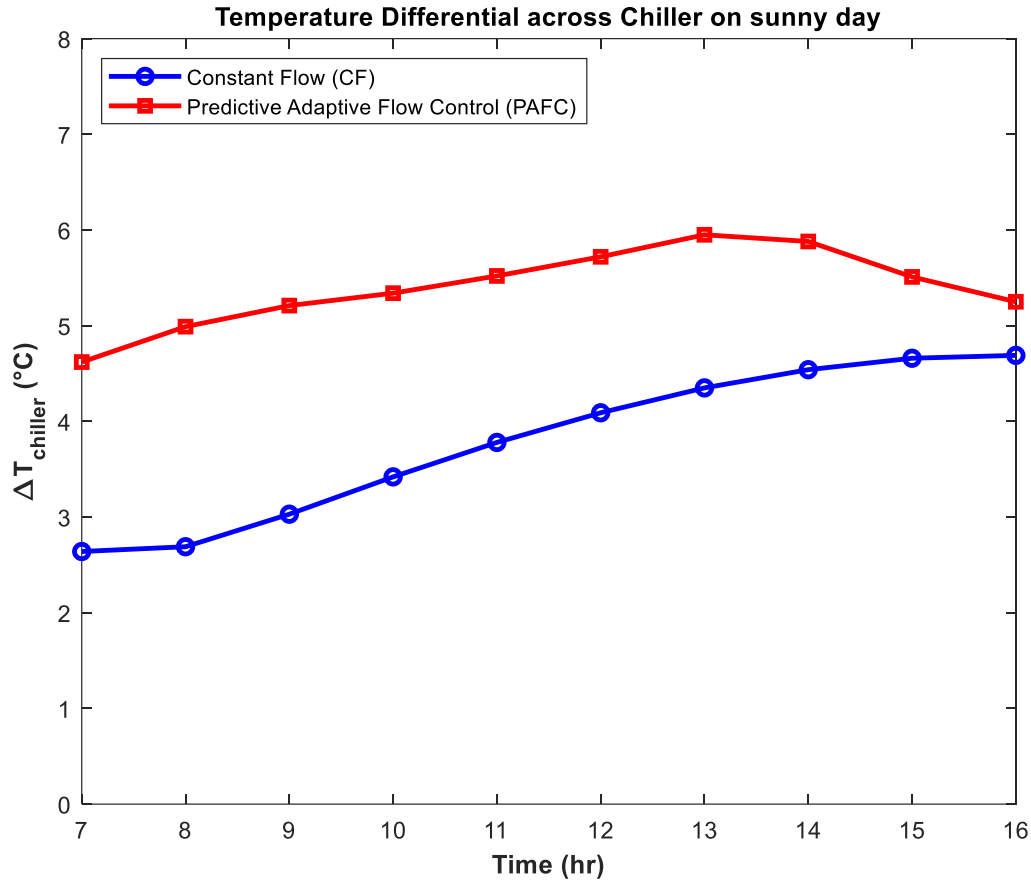


Figure 4.16. Comparison of the system Delta-T on typical sunny day

The higher delta-T observed under PAFC operation has important system design and operational implications. It enables the use of smaller diameter piping and pumps, reducing capital investment and ongoing maintenance costs. Moreover, it supports more precise temperature control and enhances the flexibility and responsiveness of the cooling system to dynamic load conditions.

Overall, while PAFC demonstrates benefits on both cloudy and sunny days, the magnitude of energy savings and efficiency improvements tends to increase with load variability, such as on sunny days with more pronounced cooling demand fluctuations. The evidence supports the adoption of intelligent, predictive flow control strategies like PAFC as best practice in modern

4.4.5 Annual Energy and Water Consumption Analysis

To evaluate the monthly and annual performance of chilled water plants it crucial to assess the climatic and indoor environmental conditions that drive cooling demand. Analyzing these climatic and indoor temperature profiles is critical in order to establish the baseline thermal loads that the chilled water plant must accommodate.

Table 4.1 presents the monthly average solar irradiance with the corresponding monthly averaged maximum indoor temperatures for a case study building located in Kuala Lumpur, simulated using TRNSYS 18. Kuala Lumpur's tropical climate results in relatively consistent solar irradiance values throughout the year, ranging from 3.83 kWh/m²/day in December to 4.67 kWh/m²/day in March. Indoor temperatures likewise remain elevated year-round, fluctuating narrowly between 31.04°C and 32.82°C, indicating a steady and continuous cooling demand irrespective of seasonal variation.

Table 4:1. Monthly average irradiance of Kuala Lumpur and indoor temperature of block B of the university of Nottingham Malaysia observed in 2024

Month	Solar irradiance (kWh/m ² /day)	Monthly averaged maximum indoor temperature of building (°C)
Jan	3.90	31.46
Feb	4.62	32.17
Mar	4.67	32.53
Apr	4.46	32.51
May	4.34	32.82
Jun	4.39	32.80
Jul	4.33	31.85
Aug	4.41	32.20

Sep	4.33	32.20
Oct	4.32	31.43
Nov	3.96	31.04
Dec	3.83	31.43

Table 4.1 reveal that the highest indoor temperatures occur from March to June, with a peak of 32.82°C in May, despite solar irradiance in May (4.34 kWh/m²/day) being slightly lower than that in March (4.67 kWh/m²/day). This discrepancy suggests that indoor thermal loads are influenced not solely by instantaneous solar gains but also by cumulative effects such as building thermal mass, internal heat retention, and potentially reduced ventilation rates during this period. These factors, along with meteorological variables like diminished wind speeds and elevated humidity, likely exacerbate latent and sensible cooling loads (Table 4.1). The persistent indoor temperatures above 31°C even during months with lower irradiance (e.g., December) further indicate significant internal heat retention and limited passive cooling capacity. Consequently, these observations justify the need for chiller designs that incorporate features such as modular staging or thermal energy storage to effectively handle the relatively uniform, high cooling demand throughout the year.

Table 4.2 compares the monthly chilled water consumption of the plant under Predictive-Adaptive Flow Control (PAFC) and Constant Flow (CF) strategies. As seen, the CF strategy maintains a constant chilled water consumption rate of 854,256.50 kg/day throughout the year, reflecting an inflexible system that does not respond to fluctuating thermal loads. In contrast, the PAFC strategy dynamically modulates flow, with monthly consumption ranging between 408,133.19 kg/day (January) and 500,303.33 kg/day (May). This adaptive control leads to a significant reduction in chilled water consumption, with an annual average of 459,849.34

kg/day approximately 46.2% lower than the constant flow case as seen in Figure 4.17. The variability of PAFC chilled water usage demonstrates its effectiveness in matching flow rates to actual cooling demand, thereby reducing unnecessary water circulation and associated energy consumption.

Table 4:2. Chilled water consumption of the plant based on the two control strategies

Month	Chilled water consumption based on the predictive -adaptive flow control (kg/day)	Chilled water consumption based on the constant flow control (kg/day)
Jan	408133.19	854256.50
Feb	476821.40	854256.50
Mar	478341.14	854256.50
Apr	478162.42	854256.50
May	500303.33	854256.50
Jun	480418.54	854256.50
Jul	470073.37	854256.50
Aug	478860.94	854256.50
Sep	432134.48	854256.50
Oct	458822.47	854256.50
Nov	431344.14	854256.50
Dec	424776.70	854256.50
Annual average	459849.34	854256.50

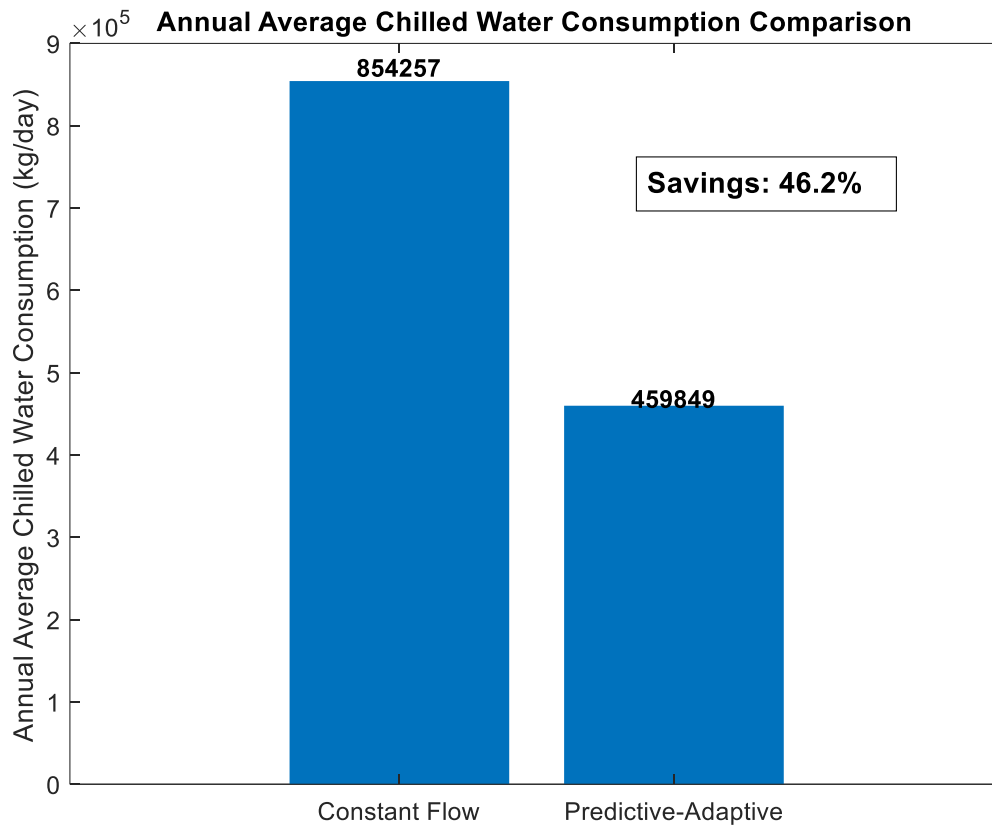


Figure 4.17. Annual averaged daily total chilled water consumption comparison of the chiller plant

The impact of the two flow control strategies on energy consumption is shown in Tables 4.3 and 4.4. Under PAFC Table 4.3, pump power consumption varies seasonally, from 50.7 kWh/day in January to 62.2 kWh/day in May, while chiller power consumption ranges from 1,248.0 kWh/day to 1,759.6 kWh/day. The total power consumption peaks at 1,821.8 kWh/day in May, correlating with the highest cooling demand. The annual average total power consumption under PAFC is 1,510.6 kWh/day, reflecting efficient modulation of both pumping and chiller operations according to load variations.

Table 4:3. Power consumption of the chilled water plant based on the predictive-adaptive flow control

Month	Pump power consumption (kWh/day)	Chiller power consumption (kWh/day)	Total power consumption (kWh/day)
Jan	50.7	1248.0	1298.7
Feb	59.3	1588.8	1648.1
Mar	59.5	1619.0	1678.5
Apr	59.4	1613.8	1673.2
May	62.2	1759.6	1821.8
Jun	59.7	1622.1	1681.8
Jul	58.4	1553.7	1612.1
Aug	59.5	1603.9	1663.4
Sep	53.7	1358.5	1412.2
Oct	57.0	1501.4	1558.4
Nov	53.6	1333.4	1387.0
Dec	52.8	1325.4	1378.2
Annual average	57.2	1510.6	1567.78

Table 4:4. Power consumption evaluation of the chilled water plant based on the constant flow control

Month	Pump power consumption (kWh/day)	Chiller power consumption (kWh/day)	Total power consumption
Jan	106.2	3098.1	3204.3
Feb	106.2	3175.3	3281.5
Mar	106.2	3218.1	3324.3
Apr	106.2	3240.3	3346.5
May	106.2	3330.9	3437.1
Jun	106.2	3229.9	3336.1
Jul	106.2	3184.1	3290.3
Aug	106.2	3195.2	3301.4
Sep	106.2	3125.8	3232.0

Oct	106.2	3184.0	3290.2
Nov	106.2	3090.9	3197.1
Dec	106.2	3099.1	3205.3
Annual average	106.2	3181.0	3287.18

Conversely, the CF strategy (Table 4.4) exhibits constant pump power consumption at 106.2 kWh/day, independent of load, while chiller power consumption fluctuates modestly between 3,090.9 kWh/day and 3,330.9 kWh/day. The total power consumption peaks at 3,437.0 kWh/day in May with an annual average of 3,287.1 kWh/day. These values underscore the inefficiency of constant flow control, which leads to excessive energy consumption regardless of actual demand.

4.5 Comparative evaluation and environmental implications

4.5.1 Comparative Energy Savings and Efficiency Implications

A comparison of the two strategies reveals that PAFC achieves a total energy saving of approximately 54% relative to CF, equivalent to 1,776.5 kWh/day in absolute terms. This substantial reduction in energy consumption is primarily due to PAFC's ability to minimize pumping energy through adaptive flow control and improve chiller efficiency via better load matching and reduced cycling. The consistently lower chiller power consumption under PAFC as seen in Figures 4.13, Figure 4.14 and Figure 4.17 also indicates enhanced thermodynamic performance and reduced mechanical wear.

Figures 4.18 and Figure 4.19 shows the monthly variations in chiller and pump power consumption, respectively, highlighting the energy-saving potential of PAFC across all months. Figure 4.20 presents the total power consumption savings, clearly showing the marked reduction achieved by adaptive flow control. Figure 4.21 is the benefits through annual

averaged daily power consumption comparisons, confirming PAFC's superiority in energy efficiency.

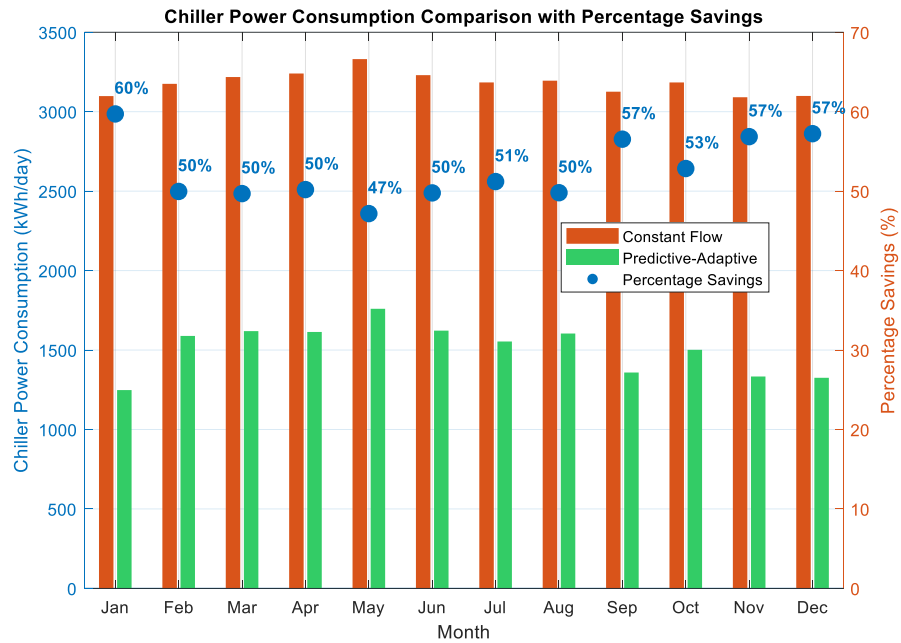


Figure 4.18. Monthly averaged daily chiller power consumption and savings analysis of the chiller plant

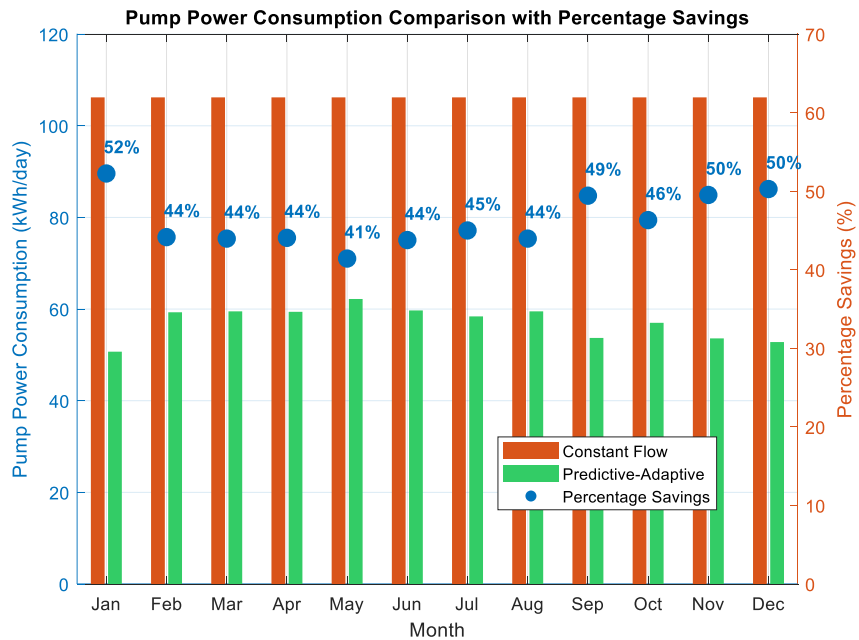


Figure 4.19. Monthly averaged daily chiller pump power consumption and savings analysis of the chiller plant

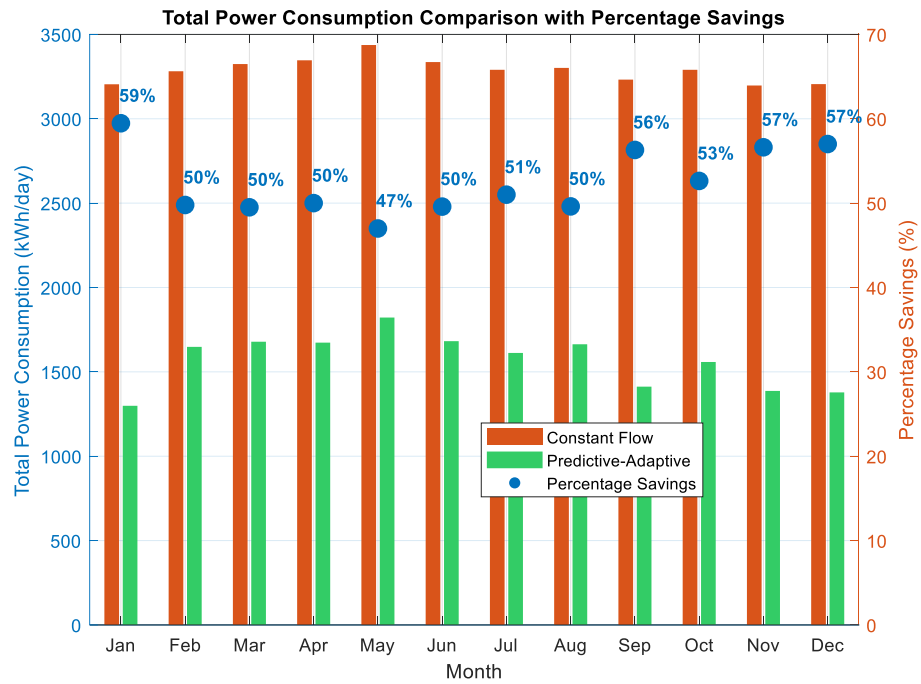


Figure 4.20. Monthly averaged daily total power consumption and savings analysis of the chiller plant

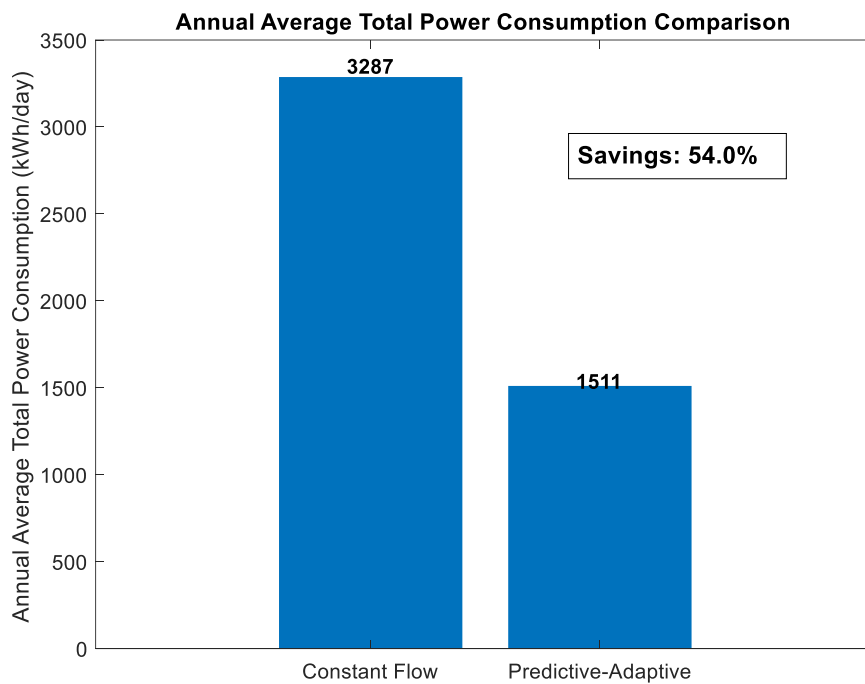


Figure 4.21. Annual averaged daily total power consumption comparison of the chiller plant

The discrepancy between chilled water consumption savings (46.2%) and total power consumption savings (54%) observed under PAFC arises from the nonlinear relationship between flow rates and pump power consumption governed by the pump affinity laws. Specifically, pump power varies approximately with the cube of the flow rate, meaning that a modest reduction in flow results in a disproportionately larger decrease in energy consumption. This cubic dependency amplifies pump energy savings beyond the linear reduction in chilled water volume.

In addition to pumping energy benefits, the modulation of chilled water flow positively impacts chiller performance. Maintaining optimal flow rates improves heat exchanger effectiveness, reduces compressor cycling, and enhances the chiller's coefficient of performance, thereby lowering electrical power requirements. Consequently, total energy savings under PAFC result from the combined effects of nonlinear pump power reduction, improved chiller operation, and hydraulic optimization. This integrated effect explains why total power consumption savings exceed chilled water consumption reductions alone.

4.5.2 System Carbon Footprint assessment and comparison

The comparative analysis of the chilled water plant's monthly carbon footprint under Predictive-Adaptive Flow Control (PAFC) and Constant Flow (CF) strategies reveals significant environmental benefits associated with adaptive control methods.

The PAFC strategy exhibits substantial monthly variations in carbon emissions that correspond closely with fluctuations in cooling demand as seen in Figure 4.22. This dynamic modulation allows the system to operate closer to actual load requirements, thereby avoiding unnecessary energy consumption during periods of low demand. It is seen from Figure 4.22 that the carbon footprint under PAFC reaches its minimum in January (approximately 20,131 kg CO₂) and

peaks in May (around 28,238 kg CO₂), reflecting typical seasonal changes in cooling needs..

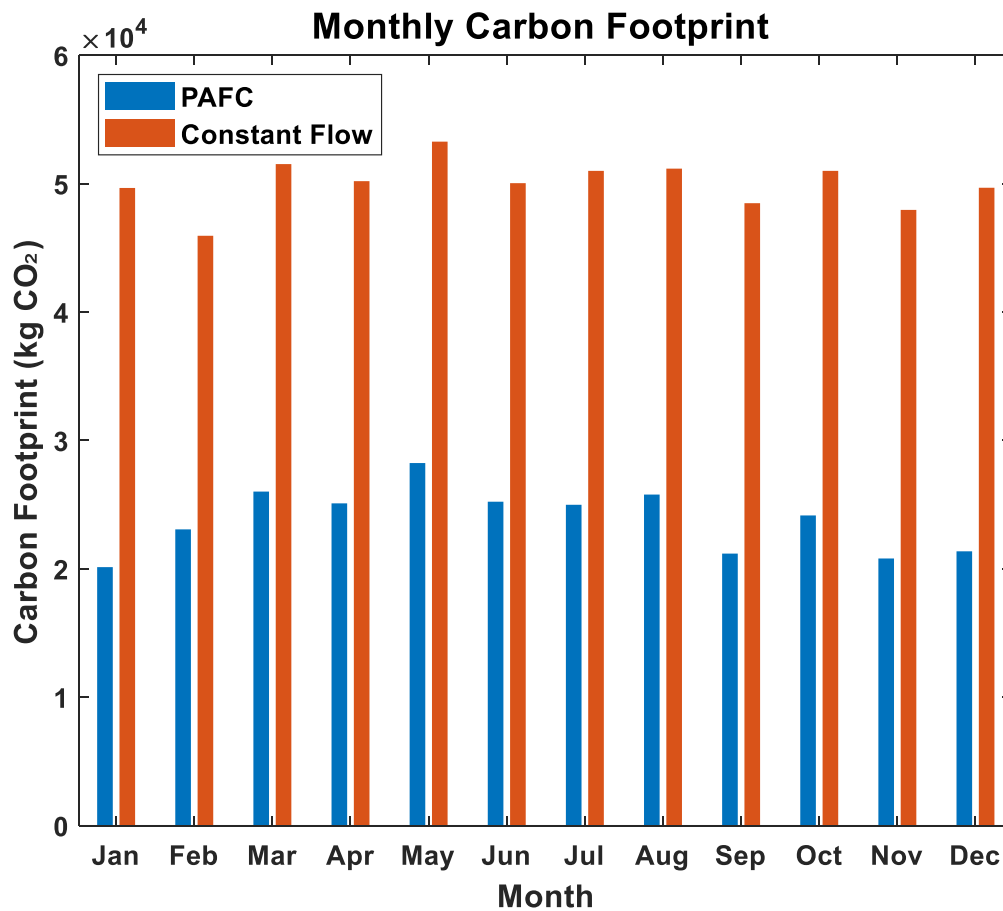


Figure 4.22. Monthly carbon footprint assessment of chilled water-cooling plant

In contrast, the CF strategy demonstrates a relatively constant and elevated carbon footprint across all months, ranging from about 47,957 kg CO₂ in November to over 53,224 kg CO₂ in May. This constancy stems from the system's inflexible operation that maintains a fixed flow rate and pump power irrespective of demand fluctuations, leading to significant energy wastage. Quantitatively, the PAFC strategy achieves an average carbon emission reduction of approximately 54% relative to CF, consistent with the observed energy savings.

From an environmental standpoint, adopting PAFC supports sustainability goals by significantly lowering greenhouse gas emissions associated with chilled water plant operations.

This reduction can contribute to organizational carbon neutrality commitments and compliance with increasingly stringent energy regulations. Furthermore, the reduction in energy consumption translates directly into lower operational costs. Given that energy expenditures typically constitute a major portion of a chilled water plant's operating budget, the savings achieved by PAFC can improve overall cost-effectiveness and return on investment.

4.5.3 Cost saving implication of the predictive-adaptive flow control method

Table 4.5 shows the monthly cost savings achieved through the application of a predictive–adaptive flow control strategy when compared with a conventional constant-flow operation, using Malaysia's electricity tariff of RM 0.221 per kWh as the basis for cost estimation. [123] The results indicate that the predictive–adaptive system significantly reduces operational costs in every month of the year, with monthly savings ranging from approximately RM 9,290 to RM 12,930. These consistent savings reflect the system's capacity to modulate flow rates according to actual thermal load requirements, thereby reducing unnecessary energy consumption that typically characterizes constant-flow systems.

Table 4:5 Monthly Cost Savings Achieved by Predictive–Adaptive Flow Control

Month	Daily Cost (RM) Constant Flow	Daily Cost (RM) Predictive-Adaptive	Daily Saving (RM)	Monthly Saving (RM)
Jan	718.30	287.30	431.00	12,930
Feb	619.00	309.40	309.60	9,290
Mar	641.00	320.50	320.50	9,615
Apr	663.00	331.50	331.50	9,945
May	751.40	397.80	353.60	10,610
Jun	729.30	364.70	364.60	10,940
Jul	707.20	353.60	353.60	10,610
Aug	718.30	359.10	359.20	10,776
Sep	696.20	309.40	386.80	11,604

Oct	718.30	342.60	375.70	11,271
Nov	729.30	364.70	364.60	10,940
Dec	729.30	364.70	364.60	10,940

The data further reveal that months with higher baseline electricity consumption under constant-flow operation such as January, May, and November to December correspond to the highest absolute financial savings under the predictive–adaptive strategy. This is expected because constant-flow systems deliver energy irrespective of real-time demand, leading to inefficiencies during periods of elevated thermal load. In contrast, predictive–adaptive control algorithms optimize energy delivery and match it closely with dynamic environmental and operational conditions. This demand-responsive operation aligns with findings from research by Fabiano et al. demonstrating that intelligent control strategies can reduce energy consumption by up to 39% and achieve up to 43% cost reduction . [124] Over the full annual cycle, the cumulative savings of approximately RM 129,000 underscore the economic viability of integrating predictive-adaptive control into energy-intensive systems.

Chapter 5: Conclusion and Recommendations

5.1 Summary

This study examined the energy-saving potential and operational performance of a predictive-adaptive chilled water flow control strategy implemented at the University of Nottingham Malaysia's chilled water plant, focusing on Block B as a representative office building. An integrated numerical model coupling building thermal dynamics and chilled water plant operations was developed and rigorously validated through experimental data. Two distinct flow control strategies were analysed: the conventional constant flow control currently in use and a novel predictive-adaptive flow control which dynamically adjusts chilled water flow based on individual zone cooling requirements.

Through detailed simulation and experimental investigation, key performance indicators including energy consumption, thermal comfort compliance, chilled water utilization efficiency, coefficient of performance (COP), and carbon emissions were evaluated. The predictive-adaptive flow control strategy demonstrated substantial improvements, including approximately 46% reduction in chilled water consumption, a 54% decrease in overall energy consumption, and a proportional decline in carbon footprint relative to the constant flow control baseline. Furthermore, the adaptive strategy enhanced occupant thermal comfort, maintaining indoor temperatures within the recommended comfort range for roughly 85% of operating hours, a significant increase compared to the 21% compliance observed under constant flow control. The study also highlighted notable reductions in pumping energy and improved chiller load matching facilitated by the adaptive modulation of flow rates, resulting in enhanced hydraulic and thermodynamic efficiency.

The findings revealed a cost savings achieved through the application of a predictive–adaptive flow control strategy when compared with a conventional constant-flow operation, using Malaysia’s electricity tariff of RM 0.221 per kWh as the basis for cost estimation. Over the full annual cycle, the cumulative savings of approximately RM 129,000 underscore the economic viability of integrating predictive- adaptive control into energy-intensive systems

5.2 Conclusions

The study successfully developed and validated an integrated numerical model that couples the thermal dynamics of the case study building with the operational characteristics of the chilled water plant. The model demonstrated high accuracy in simulating real-world conditions, as verified by experimental data, and provided a robust platform for evaluating different chilled water flow control strategies. This validated modelling approach enabled comprehensive analysis of the building’s cooling demand and the chilled water plant’s response under varying operational scenarios.

A predictive-adaptive chilled water flow control strategy was formulated and implemented, leveraging real-time temperature data and zone-specific thermal capacitance to estimate precise cooling requirements for each thermal zone. This control strategy effectively modulated the chilled water flow to match actual cooling loads, thereby optimizing energy consumption and minimizing the risk of overcooling. The adaptive control algorithm coordinated flow distribution across multiple zones, ensuring balanced thermal comfort while improving overall system efficiency.

Comparative analysis between the predictive-adaptive control strategy and the conventional constant flow control demonstrated the significant advantages of the adaptive approach. The predictive-adaptive strategy yielded approximately 46% reduction in chilled water

consumption and a 54% decrease in total energy use. It also enhanced thermal comfort compliance, maintaining indoor temperatures within the recommended comfort range for approximately 85% of scheduled operating hours, compared to only 21% for the constant flow system. These improvements are attributable to the adaptive system's ability to dynamically align chilled water flow with real-time cooling demands, resulting in reduced pumping energy, better chiller load matching, and lower greenhouse gas emissions.

The findings of this research confirm that individual space predictive-adaptive chilled water flow control provides a viable and effective solution for improving the energy efficiency and occupant comfort of chilled water-cooling systems in commercial buildings.

The analysis demonstrates that implementing a predictive–adaptive flow control strategy yields significant economic and operational advantages compared with the conventional constant-flow approach. Using Malaysia's electricity tariff of RM 0.221 per kWh as the benchmark for cost estimation, the strategy delivered an annual cumulative cost savings of approximately RM 129,000. This magnitude of savings highlights the strong economic justification for integrating predictive–adaptive control into energy-intensive chilled water systems.

Beyond the financial benefits, the associated reductions in energy consumption and carbon emissions emphasise the broader sustainability value of intelligent control methodologies. By enhancing system responsiveness to dynamic load and environmental conditions, predictive–adaptive control not only improves operational efficiency but also aligns with contemporary goals of reducing environmental impact in the HVAC sector.

5.3 Recommendations

Based on the findings of this study, it is recommended that commercial and institutional buildings with centralized chilled water systems consider implementing predictive-adaptive

flow control strategies to optimize energy consumption and improve occupant comfort. Building managers and facility engineers should prioritize retrofitting existing constant flow systems with intelligent control algorithms that dynamically adjust chilled water flow in response to real-time thermal loads at individual zones. This approach not only enhances system efficiency but also reduces operational costs and greenhouse gas emissions, contributing to broader sustainability goals.

It is further recommended that future system designs incorporate advanced sensor networks and robust communication infrastructure to support the accurate measurement and timely transmission of zone temperature data, which are critical for the successful deployment of adaptive flow control. Stakeholders should also invest in comprehensive training programs to ensure facility personnel are equipped to manage and maintain these more sophisticated control systems effectively.

Moreover, it is advisable that energy management policies at institutional levels encourage the adoption of adaptive chilled water flow control through incentives, guidelines, and performance standards. Integrating such strategies into building codes and energy certification programs could accelerate their widespread implementation and amplify the environmental and economic benefits.

Finally, given the potential variations in building usage, occupancy patterns, and climatic conditions, it is recommended that adaptive flow control systems be tailored and calibrated for each building's unique characteristics. Continuous monitoring and periodic recalibration should be established as best practices to maintain optimal system performance over time.

5.4 Suggestions for Future Research

Despite the positive outcomes of this study, several limitations must be acknowledged. The research was conducted on a single office building situated in a tropical climate, which may restrict the generalizability of the findings to other building types or climatic regions without further validation. The thermal model incorporated certain simplifying assumptions, such as fixed occupancy schedules and homogeneous material properties, which might not fully capture the complexity and variability encountered in real-world environments. Additionally, the experimental validation utilized a scaled prototype facility, potentially limiting the extent to which these results reflect full-scale building operations. The control system was also based on ideal conditions with accurate sensors and negligible communication delays, factors that may vary in practical applications and affect control performance.

Future research should seek to address these limitations by expanding the scope of investigation to include diverse building typologies and climatic zones, thereby testing the robustness and adaptability of the predictive-adaptive chilled water flow control strategy under a wider range of conditions. There is also considerable potential in exploring more sophisticated control algorithms, such as those based on machine learning or artificial intelligence, which could improve prediction accuracy and system responsiveness by learning occupant behaviour and environmental dynamics in real-time. Further studies could investigate the integration of such adaptive control systems with renewable energy sources and thermal energy storage solutions to enhance sustainability and operational flexibility. Long-term field trials in operational buildings would provide critical insights into the durability, user acceptance, and real-world energy savings of these control strategies over extended periods. Additionally, comprehensive economic and lifecycle assessments would be valuable to quantify the cost-effectiveness and environmental impacts of widespread implementation. Finally, advancements in sensor

technology and communication networks should be pursued to ensure reliable, low-latency control capable of meeting the demands of complex and large-scale chilled water systems.

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