

HYDRAULIC CONFIGURATION ANALYSIS OF CHILLER-BASED COOLING SYSTEMS

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Abstract. Hydraulic imbalance in chilled water systems remains one of the most underestimated causes of reduced cooling capacity, degraded part-load efficiency, and excessive energy consumption in commercial buildings. Although modern chillers, variable-speed drives, and advanced control algorithms have significantly improved nominal equipment efficiency, real plant performance is frequently constrained by improper flow distribution, uncontrolled mixing, and degradation of the system temperature difference (ΔT) under partial load operation. This study applies a comparative analytical methodology to investigate the relationship between hydraulic configuration, return water temperature, and chiller efficiency in three commonly used chilled water system concepts: constant primary and secondary flow, constant primary and variable secondary flow (primary–secondary), and variable primary flow systems. The analysis focuses on hydraulic interaction between production and distribution circuits, ΔT behavior, flow stability, and chiller loading under full-load and part-load conditions. Using a representative annual cooling load duration profile and a 500 kW chiller as a reference case, seasonal energy consumption and efficiency trends are quantified. The results demonstrate that constant-flow systems are inherently prone to low- ΔT syndrome, while primary–secondary systems remain sensitive to hydraulic decoupler mixing. Variable primary flow systems consistently maintain higher return temperatures, enable effective hydraulic unloading, and achieve the lowest annual electricity consumption. The findings confirm that hydraulic design and flow control strategy are decisive factors for seasonal chiller efficiency, exceeding the influence of nominal chiller performance ratings.

Keywords: chiller plants, hydronic imbalance, hydraulic balancing, mixing loops, primary–secondary systems, variable primary flow, low- ΔT syndrome, constant flow.

1. Introduction

Part-load operation and low ΔT syndrome in chiller plants

Chillers are typically sized to satisfy extreme design conditions determined by the climatic context of the installation. Such conditions occur for a very limited portion of the annual operating period. Consequently, chiller plants operate under partial-load conditions for the vast majority of their service life.

Under partial-load operation, chiller systems are prone to the occurrence of low temperature difference (ΔT) syndrome, a condition that significantly degrades chiller performance. Low ΔT operation leads to reduced thermal efficiency, frequent compressor cycling, and limitations on effective chiller loading.

Low ΔT syndrome arises when the chilled water return temperature supplied to the chiller is lower than

the design value. Low ΔT syndrome, a pervasive issue in chiller plants operating under partial-load conditions, impacts energy efficiency and operational stability (Gao et al., 2015).

Specifically, this phenomenon, characterized by a reduced temperature difference between the chilled water supply and return, leads to increased flow rates and diminished thermal transfer effectiveness (Van den Brink et al., 2023).

This syndrome is particularly problematic in conventional chiller plants, which are typically sized for peak loads but operate predominantly at partial loads, leading to inefficient operation for the majority of their service life (Wan et al., 2024). The resulting energy penalties can be substantial, with studies indicating a potential decrease in operating efficiency by 30–40% under these conditions, making it a critical area for energy conservation efforts in commercial

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and industrial buildings (Hinkelman et al., 2021; Chen et al., 2022).

Impact of overflow and pump control on terminal units performance

Water-based Terminal units (TUs) for cooling are typically designed for a temperature differential (ΔT) of 5 K, achieving nominal thermal output at design flow rate with a chilled water supply temperature of 7 °C and a return temperature of 12 °C. Under these conditions, the rated thermal capacity corresponds to 100% flow through the terminal unit. Excess flow through the TU has a limited direct effect on instantaneous thermal output. However, a more critical effect arises from the influence of elevated flow rates on heat transfer characteristics. Increased flow enhances heat transfer within the coil, resulting in a return water temperature that is significantly lower than the design value (Figure 1).

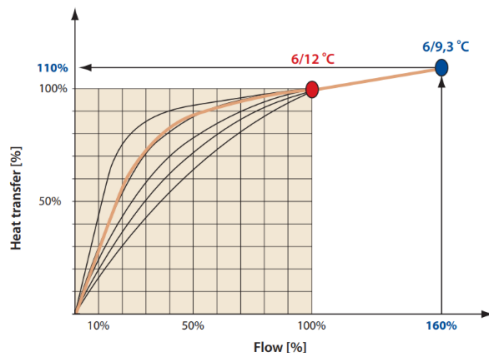


Figure 1. Impact of increased flow rate on heat transfer and ΔT degradation (source: Danfoss, 2014)

This reduction in return temperature contributes directly to the development of low ΔT syndrome at the system level. This issue is exacerbated by situations such as overflow conditions in chilled water systems, often resulting from oversizing of pumps or lack of proper balancing valves, which further contribute to inefficient chiller plant operation (Retezan & Ehrenberg, 2019). This low ΔT condition, characterized by a reduced temperature difference between supply and return water, is a commonly observed issue in energy transfer stations (Zafar & Özçelik, 2024). This phenomenon is frequently a consequence of oversized pumping systems, which circulate excessive chilled water through the coils, leading to suboptimal heat exchange and consequently, a lower return water temperature than initially designed (Liu et al., 2024). This excess flow not only diminishes the temperature differential but also increases pumping energy consumption, thereby reducing the overall efficiency of the chiller plant.

Constant primary and secondary flow system

The constant primary and secondary flow system represents one of the most traditional hydraulic configurations used in commercial chiller applications (Figure 2). In this arrangement, constant-flow chillers are applied, and the circulation pumps are designed to deliver a fixed flow rate under all operating conditions. Proper water distribution among chillers requires the installation of manual balancing valves (MBVs) on each chiller branch.

A fundamental limitation of this configuration is that chiller staging is not feasible. All chillers must operate simultaneously to maintain the required system flow, even under partial-load conditions. This excessive flow contributes to low ΔT syndrome, as the increased flow rate through heat exchangers at reduced loads leads to a smaller temperature differential and diminished chiller efficiency (Thangavelu et al., 2017).

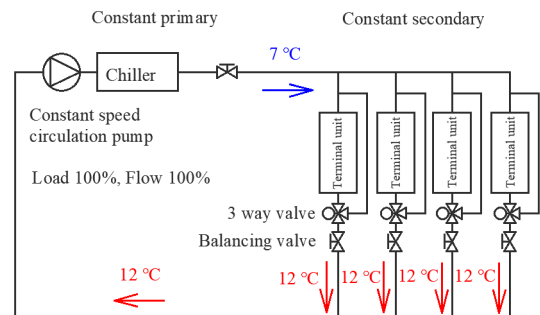


Figure 2. Constant flow cooling system

From an operational standpoint, the defining requirement of constant flow systems is that the flow through each chiller must be maintained at all times. Any deviation below the minimum allowable flow rate triggers chiller protection functions, such as low-flow alarms, leading to automatic shutdown.

Constant primary and variable secondary flow system (primary–secondary configuration)

The constant primary and variable secondary (primary–secondary) system represents an evolutionary step from fully constant-flow configurations and has been widely adopted in commercial chiller plants (Figure 3). In this arrangement, the primary circuit operates at constant flow, supplying chillers with a fixed design flow rate, while the secondary circuit operates with variable flow, adapting to changing load conditions at the terminal units. This configuration requires separate primary and secondary circulation pumps. For effective chiller staging, motorized isolation valves and MBVs are typically installed on each chiller branch.

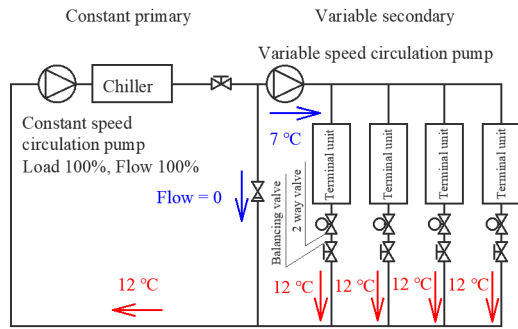


Figure 3. Constant primary and variable secondary cooling system

The hydraulic decoupler (by-pass) plays a central role in preventing direct interaction between the primary and secondary circuits. This decoupling allows the primary pumps to maintain a stable differential pressure across the loop, while secondary pumps can modulate their speed to match the varying cooling demands of the building zones. This setup enables an independent optimization of each circuit, allowing primary pumps to ensure flow requirements for chillers while secondary pumps adjust to the actual cooling load, thus enhancing overall system efficiency and responsiveness. Under ideal conditions, this allows independent control of chiller flow and distribution flow. However, under partial-load operation, the decoupler can become a source of uncontrolled mixing, contributing to low ΔT syndrome. Secondary pumps should be controlled based on a differential pressure (Δp) signal. Chiller control logic in primary–secondary systems is relatively simple, as chillers operate under constant-flow conditions and can be staged based on load demand.

Variable primary flow system

The variable primary flow (VPF) system represents the most advanced hydraulic configuration for modern chilled water plants (Figure 4). In this concept, both the production and distribution circuits operate under variable flow conditions, and secondary pumps are eliminated. Chillers equipped with variable-speed compressors and designed to tolerate reduced evaporator flow rates are required, resulting in higher initial equipment cost. A hydraulic bypass equipped with a pressure independent control valve (PICV) and a flow meter (FM) is installed between the supply and return headers to ensure the minimum flow required for safe chiller operation during low-load conditions. The VPF system features a simple and transparent hydraulic layout.

The inherent adaptability of VPF systems makes them particularly well-suited for dynamic building loads, facilitating substantial energy savings through optimized pump operation and precise flow control across the entire system (Retezan & Ehrenberg, 2019; Niu et al., 2023). This sophisticated approach inherently minimizes the

potential for low ΔT syndrome by ensuring that chillers consistently receive return water at design temperatures, thereby sustaining optimal thermal performance and energy efficiency.

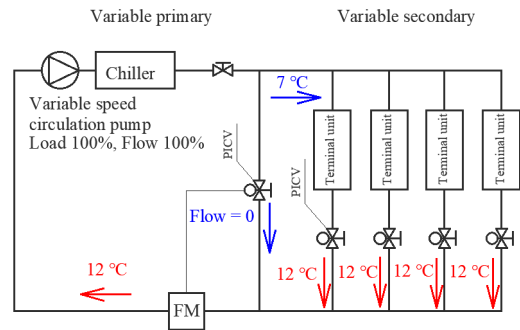


Figure 4. Variable primary and secondary cooling system

The inherent flexibility of VPF systems, which integrate variable speed drives for primary pumps and advanced control strategies, addresses the core issues leading to low ΔT syndrome by maintaining appropriate flow rates across evaporators and optimizing temperature differentials under varying load conditions, contrasting with the fixed flow limitations of constant speed primary pump systems (Kumar et al., 2021). Chillers can be staged and modulated based on optimal efficiency points at specific load ranges, rather than on fixed capacity steps.

Problem statement and research objective

Despite advances in chiller technology, variable-speed drives, and control algorithms, the operational efficiency of chilled water plants in commercial buildings often remains well below design expectations. This performance gap is primarily caused not by the chiller itself, but by hydraulic imbalance, uncontrolled flow distribution, and degradation of the chilled water temperature difference (ΔT) under part-load conditions. Low- ΔT syndrome remains widespread and leads to reduced chiller loading. Although constant-flow, primary–secondary, and variable primary flow systems are widely used, their comparative hydraulic behavior and direct impact on return water temperature and chiller efficiency under realistic part-load operation are not consistently quantified. In particular, the influence of hydraulic interaction, mixing effects, and chiller-side ΔT degradation remains insufficiently addressed.

The objective of this study is to analyze how different chilled water hydraulic configurations affect return water temperature, ΔT stability, chiller loading, and seasonal energy efficiency under part-load operation. Three common system concepts—constant primary and secondary flow, constant primary with variable secondary flow, and variable primary flow—are evaluated using a representative annual cooling load profile and a common reference

chiller capacity to identify the dominant hydraulic mechanisms responsible for low- ΔT behavior and associated energy penalties.

2. Methodology

To address the research objective defined in the preceding section, this study employs a comparative analytical methodology to investigate the hydraulic and thermal behavior of chilled water plants and to identify the mechanisms that govern system efficiency under realistic operating conditions. The focus is placed on how different system concepts behave under load variation, rather than on descriptive comparison of system layouts.

The analysis is based on a systematic comparison of three commonly applied chilled water system configurations:

- Constant primary and secondary flow (constant flow system),
- Constant primary and variable secondary flow (primary-secondary system),
- Variable primary flow system.

Each configuration is evaluated under part-load conditions, representing the predominant operating regime of commercial chiller plants.

For each system, the analytical framework examines:

- Temperature differential (ΔT) behavior, with emphasis on return temperature deviation from design values,
- Hydraulic interaction between production and distribution circuits, including mixing effects.

General relationship between return temperature and chiller efficiency

Chiller efficiency is fundamentally dependent on the temperature conditions at the evaporator, which are directly influenced by the return water temperature from the chilled water system. For a given chilled water supply temperature, the return temperature determines the effective ΔT across the evaporator and, consequently, the achievable cooling capacity and coefficient of performance (COP). Chilled water systems are typically designed for a ΔT in the range of 5–7 K under nominal operating conditions. Maintaining this design ΔT is essential to ensure correct chiller loading, stable operation, and high seasonal efficiency, as shown in Equation (1):

$$\text{CHL (\%)} = \frac{\text{CHWR}_{\text{TA}} - \text{CHW}_{\text{STD}}}{\text{CHWR}_{\text{TD}} - \text{CHW}_{\text{STD}}} \times 100, \quad (1)$$

where: CHL (%) is chiller loading percentage; CHWR_{TA} is chilled water return temperature actual (example: 9 °C); CHWR_{TD} is chilled water return temperature design (example: 12 °C); CHW_{STD} is chilled water supply temperature design (example: 7 °C).

Deviations from the design return temperature most notably reductions caused by excessive flow or hydraulic

mixing lead to low ΔT operation, which adversely affects chiller performance across all system configurations. This reduction in effective loading often necessitates additional chiller engagement or operation at suboptimal conditions, increasing overall energy consumption. Conversely, an increase in the return water temperature, while still meeting cooling demands, can lead to decreased energy input for the chiller by reducing the temperature lift between the evaporator and condenser (Sullivan et al., 2010). This nuanced relationship highlights the critical importance of maintaining optimal chilled water return temperatures to maximize chiller coefficient of performance and ensure efficient energy utilization (Arifin et al., 2023).

Use of annual cooling load profile

To evaluate the seasonal impact of different chilled water system configurations on chiller efficiency and energy consumption, a typical annual cooling load duration profile was applied as a common boundary condition for all analyzed scenarios (Figure 5). The load profile represents the distribution of operating hours as a function of relative cooling demand and reflects typical behavior of comfort cooling systems in commercial buildings, where operation at partial load dominates the annual runtime.

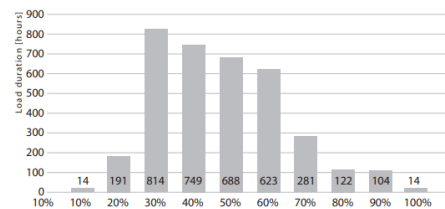


Figure 5. Annual load profile (source: Danfoss, 2020)

As illustrated (Figure 5) the majority of operating hours occur in the 30–60% load range, while full-load conditions represent only a small fraction of the total annual operating time. Commercial buildings frequently exhibit high electricity consumption attributable to HVAC systems, with chiller plants alone accounting for up to 50% of this energy usage, thereby underscoring the substantial potential for energy savings through optimized design and operation (Cheng et al., 2015). This high energy consumption is often exacerbated by conventional operation methods that maintain all equipment at design conditions, leading to substantial inefficiencies since building cooling loads fluctuate significantly over time and are often less than the design capacity (Thangavelu et al., 2017). This characteristic makes the load profile particularly suitable for assessing part-load performance, low- ΔT behavior, and chiller efficiency. The annual load profile was discretized into load bins (expressed as a percentage of nominal chiller capacity), each associated with a corresponding number of operating hours.

For each load bin, the instantaneous cooling demand was calculated based on the nominal chiller capacity. Chiller efficiency (COP) corresponding to each load level and system configuration was then applied to determine the electrical power consumption.

Annual electricity consumption was calculated using an hour-weighted summation approach, as shown in Equation (2):

$$E_{annual} = \sum(Q_{load} / COP_{load} \times t_{load}), \quad (2)$$

where: Q_{load} is the cooling demand at a given load level; COP_{load} is the corresponding chiller efficiency, and t_{load} is the annual operating time at that load.

The same annual load profile was applied consistently to all system scenarios to ensure a comparative analytical assessment under identical operating conditions. This approach allows differences in annual energy consumption and seasonal efficiency to be attributed solely to hydraulic configuration, flow control strategy, and ΔT behavior.

The analysis is intended to isolate the influence of hydraulic configuration and flow control strategy; absolute numerical results, therefore, represent typical trends rather than site-specific measured performance.

3. Results

Assumptions for all scenarios: chilled water supply temperature: $T_s = 7 \text{ }^\circ\text{C}$; design chilled water return temperature: $T_{r,design} = 12 \text{ }^\circ\text{C}$; design temperature difference: $\Delta T_{design} = 5 \text{ }^\circ\text{C}$; constant specific heat of water: $c_p = 4.18 \text{ kJ/(kg/K)}$; mass flow rate: $Q = m c_p \Delta T$; chiller nominal cooling capacity: 500 kW. Power consumption: $P_{el} = Q/COP \text{ (kW)}$.

Constant-flow system: part-load ΔT collapse and COP degradation

In this configuration, both the chiller loop and the distribution network operate under constant flow conditions. Terminal units are equipped with three-way control valves, which cause flow bypassing under part-load operation and lead to a collapse of the system temperature difference (ΔT). Pump speed remains constant, and the total system flow does not change across the entire load range (Figure 6). Based on field observations of constant-flow systems with three-way valves, representative return water temperatures, chiller coefficients of performance (COP), and electrical power consumption were calculated using the annual load profile.

In constant primary and secondary flow systems, chillers operate with a fixed evaporator flow rate under all load conditions. To quantify the influence of system ΔT on chiller efficiency, a simplified analytical framework was applied using representative operating conditions for comfort cooling systems.

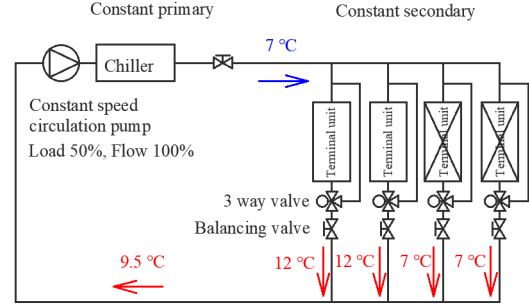


Figure 6. Constant flow system at 50% partial load condition

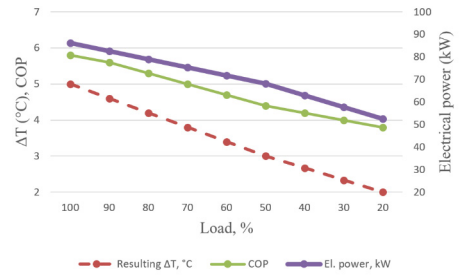


Figure 7. Impact of part-load operation on ΔT , COP, and electrical power consumption for a constant flow system

The results demonstrate that in constant-flow chilled water systems with three-way terminal valves, part-load operation leads to a rapid degradation of temperature difference and chiller efficiency. At 50% load, a ΔT reduction from 5 K to 3 K decreases COP by approximately 32%, while at 20% load, the efficiency penalty exceeds 50%. This confirms that constant-flow systems are inherently incompatible with efficient part-load operation and are highly susceptible to low- ΔT syndrome (Figure 7).

The chiller is unable to unload hydraulically under part-load conditions, resulting in a collapse of the system ΔT . The reduced ΔT directly limits the available cooling capacity and forces the chiller to operate at lower efficiency, leading to a significant increase in specific energy consumption. In real installations, this behavior often triggers premature chiller staging, causing additional machines to be brought online unnecessarily and further degrading overall plant efficiency.

Primary–secondary system: effect of hydraulic bypass on chiller-side ΔT

In the primary–secondary configuration, the chiller (primary) loop operates at constant flow provided by a constant-speed primary pump, while the secondary distribution loop is equipped with variable-speed drive (VSD) pumps that modulate flow in response to building load. The two circuits are hydraulically separated by a decoupler (by-pass), which allows independent control of production and distribution flows. Under part-load conditions, mixing reduces the temperature of the water returning to the chiller, leading to degradation of the effective temperature difference (ΔT) across the evaporator.

In primary–secondary systems (Figure 8), chillers therefore continue to operate under constant-flow conditions, while the secondary distribution system adapts to load variations. Although the hydraulic decoupler isolates the production and distribution circuits and improves operational flexibility compared to fully constant-flow systems.

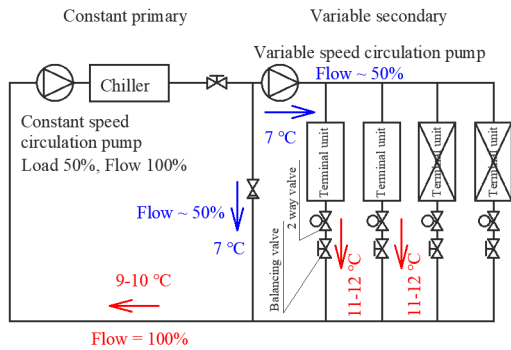


Figure 8. Constant primary and variable secondary system at 50% partial load conditions

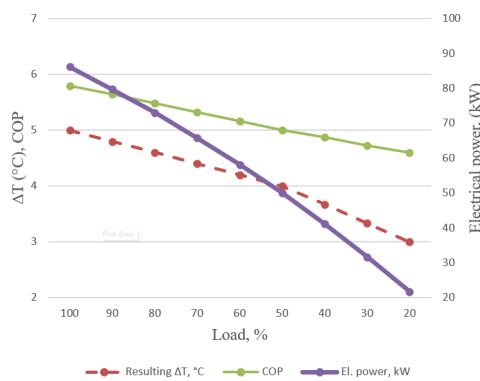


Figure 9. Impact of part-load operation on ΔT , COP and electrical power consumption for primary-constant and secondary-variable flow system

The results demonstrate that a primary–secondary system with constant primary flow and variable secondary flow, when combined with two-way control valves and proper hydraulic balancing, can maintain a significantly higher chiller-side ΔT under part-load conditions compared to constant-flow systems. By allowing the secondary flow rate to more closely follow the actual building demand, supply-to-return short-circuiting at the hydraulic decoupler is substantially reduced, resulting in higher return temperatures to the chiller and more effective unloading of the refrigeration machine. The preservation of higher ΔT at part load directly improves chiller efficiency, as evidenced by a more gradual degradation of COP with decreasing load, with performance remaining close to design values at moderate loads and clearly outperforming constant-flow operation at low loads (Figure 9). Furthermore, because the cooling capacity delivered by the chiller more accurately matches the

system demand, electrical power consumption decreases in a more proportional manner, avoiding the characteristic inefficiencies of constant-flow systems where power input remains disproportionately high despite reduced cooling demand. These findings confirm that hydraulic decoupling alone does not guarantee good part-load performance; however, when supported by variable secondary pumping, two-way valves, and correct hydraulic balancing, a primary–secondary configuration can effectively mitigate low- ΔT behavior and deliver superior part-load energy performance.

However, under partial-load conditions, the decoupler frequently becomes a source of uncontrolled thermal and hydraulic mixing. When secondary flow exceeds or falls below primary flow, return water temperatures supplied to the chillers are reduced relative to design values. Although secondary pump modulation can reduce distribution-side energy consumption, chiller efficiency remains strongly constrained by constant primary flow operation. Low return temperatures prevent chillers from reaching optimal loading levels and often cause premature staging of additional machines. As a result: low ΔT syndrome remains prevalent under part-load conditions, chiller COP and Integrated Part Load Value (IPLV) are significantly degraded, and energy savings are limited to the secondary pumping circuit.

Primary–secondary systems, therefore, represent an improvement over constant flow systems, but they do not fundamentally resolve return temperature–related efficiency losses at the chiller level.

Variable primary flow system: stable return temperature and seasonal efficiency

In the variable primary flow (VPF) configuration, system flow is regulated by a variable-speed primary pump operating under differential pressure control. Pressure-independent control valves (PICVs) or pressure-independent balancing and control valves (PIBCVs) are applied at terminal units to limit overflow and ensure stable flow distribution across varying load conditions. A minimum-flow bypass is installed to protect the chiller at low-load operation; however, it remains closed during normal part-load conditions. The bypass opens only when system flow approaches the minimum allowable limit, corresponding to approximately 20% load in this case, which is required to maintain safe operation (Figure 10).

In VPF, the system delivers the required load without ΔT collapse because flow is reduced rather than short-circuited. In the variable primary flow configuration, the primary pump is speed-controlled based on the differential pressure of the hydraulically critical circuit, and terminal flows are limited using pressure-independent control. As a result, the system maintains a stable return temperature close to the design value and preserves the design temperature difference $\Delta T \approx 5$ K across a chiller (Figure 11).

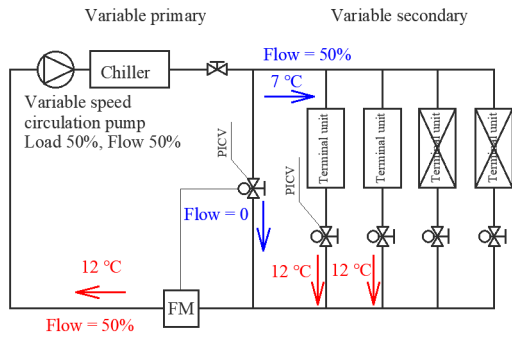


Figure 10. Variable cooling system at 50% partial load conditions

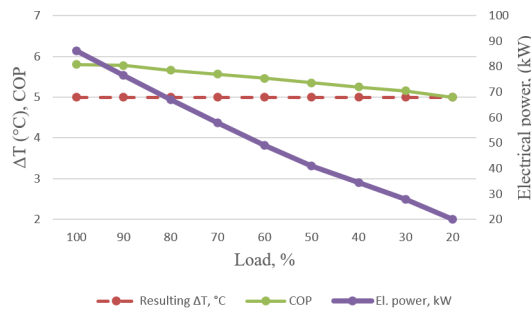


Figure 11. Impact of part-load operation on ΔT , COP and electrical power consumption for primary-variable and secondary-variable flow system

The variable primary flow system provides the most favorable operating conditions with respect to return temperature management and chiller efficiency. In this configuration, evaporator flow is allowed to vary in proportion to cooling demand, enabled by variable-speed chillers, variable-speed pumps, and pressure-independent flow control. Because both flow rate and chiller capacity are modulated, excessive flow through terminal units is avoided, and the design return temperature is maintained across a wide range of operating conditions. A bypass is used only to ensure minimum allowable chiller flow under extreme low-load scenarios and remains closed during most normal operation.

Annual consumption comparison

The annual electricity consumption analysis compares three chiller hydraulic configurations under an identical load-duration profile. The constant-flow system exhibits the highest annual electricity use, reaching approximately 392 MWh/year, reflecting significant efficiency degradation under part-load operation. Introducing a constant primary-variable secondary configuration reduces annual consumption to about 299 MWh/year, corresponding to an energy saving of roughly 93 MWh/year (–23.8%) compared to the constant-flow baseline. This reduction is primarily attributed to improved flow control on the secondary side and a higher maintained temperature difference across the chiller (Figure 12).

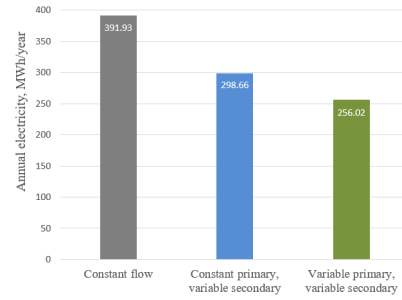


Figure 12. Annual electricity consumption of a 500 kW chiller for three hydraulic configurations under the same load-duration profile.

The fully variable primary and secondary configuration delivers the lowest annual electricity consumption, approximately 256 MWh/year, achieving total savings of about 136 MWh/year (–34.7%) relative to the constant-flow system (Table 1). In addition to reducing energy use, this configuration attains the highest seasonal performance. Overall, the comparison demonstrates that increasing the degree of flow variability and improving hydraulic control enhances part-load performance and leads to annual energy savings.

Table 1. Annual electricity consumption, seasonal performance, and savings (500 kW chiller)

Scenario	Annual electricity (MWh/year)	Annual MWh saving vs constant flow	Annual COP	COP change vs design (5.8)
1) Constant flow	391.93	—	4.63	–20.2%
2) Constant primary, variable secondary	298.66	93.27	5.14	–11.4%
3) Variable primary, variable secondary	256.02	135.91	5.45	–6.00%

Compared to the constant-flow baseline, the constant primary-variable secondary configuration saves approximately 93 MWh/year, while the fully variable-flow system achieves savings of about 136 MWh/year, together with the highest seasonal COP.

Annual (seasonal) COP for three chiller hydraulic configurations: constant flow, constant primary with variable secondary flow, and fully variable primary and secondary flow, is presented in Figure 13.

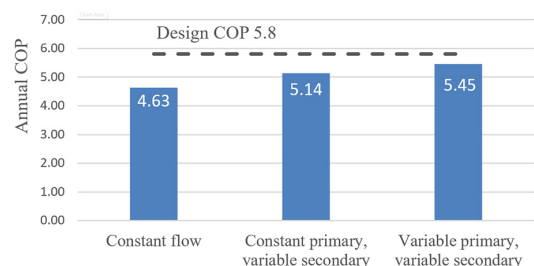


Figure 13. Annual COP comparison for different chiller hydraulic configurations

The dashed horizontal line represents the design COP of 5.8. Results are based on the same load-duration profile and illustrate the effect of hydraulic configuration on part-load efficiency and overall seasonal performance.

4. Conclusions

This study demonstrates that hydraulic behavior, rather than chiller technology alone, governs the real efficiency of chilled water plants. The conclusions are based on a comparative analytical assessment using representative operating assumptions, performance characteristics, and an annual cooling load profile, rather than on direct field measurements. Across all analyzed system configurations, degradation of the temperature difference (ΔT) under part-load conditions emerged as the primary mechanism driving reduced chiller loading, elevated specific energy consumption.

Constant flow systems with three-way terminal valves were shown to be structurally incompatible with efficient part-load operation, as they inherently promote bypassing and return temperature collapse. Primary–secondary systems improve operational flexibility; however, they remain highly sensitive to hydraulic decoupler behavior and differential pressure (ΔP) definition. Even when system-side ΔT is preserved, chiller-side ΔT can be significantly reduced due to temporary supply-to-return mixing, resulting in measurable seasonal efficiency penalties.

Hydraulic imbalance emerges as the dominant root cause of low- ΔT syndrome in the analytical scenarios considered, outweighing chiller technology differences across all analyzed system configurations.

Constant flow systems with three-way terminal valves inherently degrade ΔT at part load, leading to reduced chiller loading, elevated specific energy consumption, and the highest annual electricity use (+34.7% vs VPF).

Primary–secondary systems are highly sensitive to hydraulic decoupler behavior; even when the system-side ΔT is maintained at design values, temporary supply-to-return mixing in the decoupler significantly reduces chiller-side ΔT and seasonal COP.

Maintaining system ΔT alone is insufficient; preserving chiller-side ΔT is critical to avoid efficiency losses caused by constant primary flow and decoupler mixing.

Annual performance is governed by part-load operation, not design-point COP; load duration weighting reveals energy penalties that are not visible in steady-state or nominal calculations.

Future work

To extend and validate the analytical findings of this study, the following research directions are proposed:

Experimental validation. Laboratory or pilot-scale testing of representative system configurations to experimentally verify ΔT behavior, flow stability, and chiller efficiency under controlled conditions.

Field measurement campaigns. Long-term monitoring of operational chilled water plants, focusing on ΔT , flow distribution, pump power, and kW/ton, to quantify the real-world impact of hydraulic design choices.

AI-based optimization frameworks. Investigation of artificial intelligence and machine-learning methods for plant optimization, applied only after hydraulic stabilization, to avoid compensating for fundamentally incorrect system behavior.

These future research activities will strengthen the link between theoretical analysis, practical engineering design, and data-driven optimization, supporting the development of high-performance and resilient chilled water systems.

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