

A Review Paper on Thermal Performance Evaluation of Water-Cooled Glycol Chiller with Different Coolant Compositions and Optimization Strategies

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Abstract — Water-cooled chillers combined with additional glycol loops are heavily used across assorted and manifold industries, comprising food processing, data centers, and trade-related HVAC systems. The addition of antifreeze agents like Ethylene Glycol (EG) and Propylene Glycol (PG) introduces meaningful changes in thermophysical attributes, leading to adjusted heat transfer coefficients and increased pumping penalties. This review paper synthesizes present-day and recent inquiry on the performance of minor coolants, assessing the thermodynamic and hydraulic impacts of diverse and assorted glycol compositions. Furthermore, it examines advanced methods to augment chiller productivity, similar as the application of ternary mixtures, the integration of nanoparticles to formulate high-conductivity nanofluids, and the implementation of data-driven predictive control algorithms. By analyzing methodologies spanning from experimental test rigs to mixed-integer nonlinear derivable predictive control (MI-DPC), this paper creates an exhaustive and inclusive framework for optimizing water-cooled glycol chillers. The results provide crucial insights into achieving ideal and perfect trade-offs between freeze protection, thermal productivity, and overall system Coefficient of Performance (COP).

Keywords: Water-Cooled Glycol Chiller, Thermal Performance, Ethylene Glycol, Propylene Glycol, Predictive Control, Nanofluids, Coefficient of Performance (COP).

I. INTRODUCTION

Water-cooled chillers represent the backbone of sizable trade-related HVAC systems and industry-related process cooling plants owing to their better thermodynamic productivity compared to air-cooled units. In several vital operations similar as milk pasteurization, beer brewing, beverage bottling, pharmaceutical batch reaction cooling, chemical crystallization, and sub-zero cold storage-the required process fluid temperatures fall near or adequately below the freezing point of pure water (0° C to -15° C). To avoid catastrophically freezing and rupturing evaporator tubes or plate packs, antifreeze solutions known as supporting operation fluids or coolants are required. The most common additional coolants are aqueous solutions of Ethylene Glycol (EG) and Propylene Glycol (PG).[1]

In automobile-related engine cooling, flat-tube louvered-fin radiators are commonly used. Experimental performance comparisons between 30/70 and 50/50 EG-water mixtures against PG-water mixtures disclose that while water achieves the greatest heat rejection rates, rising glycol concentrations proportionally decreases thermal performance. Notably, 50/50 PG/water mixtures produced up to 11.46% reduced radiator heat rejection rates compared to pure water. However, PG is frequently preferred over EG due to its reduced toxicity and nature-related safety, justifying the minimal reduction in thermal performance.[9]

II. LITERATURE REVIEW

A. Thermophysical Properties and Heat Exchanger Dynamics

The correct thermal evaluation of a glycol chiller system hinges upon temperature- and concentration-dependent fluid characteristics. Based on the ratio of glycol to water, core and foundational attributes similar as dynamic viscosity, explicit and defined heat capability, and thermal conductivity undergo substantial modifications. As glycol concentration increases, the fluid 's viscosity rises exponentially at low temperatures (as earlier charted). This advancement in viscosity not just increases the frictional pressure drop; thereby requiring greater pumping power; but furthermore, suppresses the convective heat transfer coefficient within the heat exchanger tubes, finally degrading the overall thermal performance of the system.

B. Antifreeze and Ternary Coolant Mixtures

To optimize the freezing point depression without incurring serious viscosity penalties, researchers have analyzed ternary coolant mixtures containing water, glycols, and salts. The addition of Sodium Chloride (NaCl) alongside EG or PG shows a synergistic effect on freezing point depression. Studies show that ternary mixtures need less EG/PG for a cost-effective formulation. For case, a mixture of EG and RO water with 5% NaCl achieves a maximum freezing point depression of -16.5° C. In conditions of percentage weight basis, NaCl is almost twice as effective as EG as a freezing point depressant because it dissociates into two ionic species. The influence of these ternary mixtures extends to the microscopic level during freezing. Experiments analyzing the effect of salt and glycol on ice crystal nucleation show that adding NaCl acts as a nucleating agent, effectively concluding the supercooling state and initiating freezing previously. Conversely, propylene glycol lowers the ice adhesion force and prevents ice crystal agglomeration. The degree of subcooling is extremely sensitive to these additives; a solution containing 6% PG and 1% NaCl attained an extremely low subcooling degree of 0.1° C. This shows that multi-component blends can be finely tuned to serve as outstanding phase change materials (PCMs) for cold thermal energy storage.[8]

C. Nanofluids for Thermal Enhancement

To counteract the decline in thermal conductivity triggered by glycol addition, new studies have investigated dispersing nanoparticles into the base fluid. Statistical linear regression analysis on ethylene glycol-based nanofluids containing alumina (Al₂O₃), titania (TiO₂), copper oxide (CuO), and carbon nanotubes (CNT) discloses that thermal conductivity increases linearly with nanoparticle concentration. The experimental results align closely with Maxwell 's effective

moderate theory. However, the dispersion of particles like CuO frequently exceeds Maxwell's predictions, potentially due to agglomeration effects producing percolation networks. While nanofluids considerably boost thermal performance, difficulties persist regarding suspension stability and increased pumping power due to greater density.[6]

D. Data-Driven and Predictive Control Optimization

Beyond fluid alterations, system-level optimization via advanced control plans is gaining prominence. Traditional rule-based control (RBC) frequently fails to dynamically adapt to changing outside conditions. Recent data-driven approaches leverage machine learning and wealthy sensor data to predict cooling loads and optimize equipment sequencing. In Singapore, a study using man-made neural networks (ANN) alongside data enrichment schemes demonstrated that constructing module-wise power prediction models (employing Polynomial Regression for pumps/fans and Multilayer Perceptrons for chillers) can optimize Variable Speed Drive (VSD) settings in real-time, achieving over 7% daily power savings.

Improving the accuracy of the predictive load is undeniably significant for model predictive control (MPC). The incorporation of feature engineering techniques, similar as K-means clustering on multi-dimensional weather data (temperature, humidity, wind speed) and Kalman filtering to eradicate noise in past load data, drastically reduces model error.

For intricate multi-chiller plants involving both discrete staging (on/off) and continuous setpoint control, conventional Mixed-Integer Model Predictive Control (MI-MPC) suffers from combinatorial explosion, rendering real-time execution intractable. An original solution is Mixed-Integer Differentiable Predictive Control (MI-DPC), which reformulates the ideal control problem as a derivable program. By employing derivable rounding and binary-variance regularization, offline self-supervised learning can synthesize explicit neural control policies. In data center cooling applications, MI-DPC demonstrated up to 11% energy savings over heuristic rule-based controllers while executing orders of magnitude quicker than traditional MI-MPC solvers.[3,8]

E. Topology and Structural Design Optimization

At the component level, the physical layout of the heat exchanger channels dictates pressure drop and thermal transfer. Topology optimization methodology applied to two-fluid heat exchange systems provides creative design pathways outside conventional production restrictions. By applying a density-based approach where a one design variable area denotes two distinct fluids separated by a solid wall, mixing is prevented without sophisticated and multifaceted penalty schemes. Through three-dimensional number-based modeling, it was found that complicated and intricate, steadily curved, and branched flow channels considerably increase the heat transfer area without incurring the keen bends that generate high pressure drops. Furthermore, counter-flow configurations generated via topology optimization attain significantly greater total heat transfer compared to uncomplicated and elementary parallel-flow reference designs.[6]

III. METHODOLOGY

To achieve the stated objectives, a rigorous, sequential experimental methodology is adopted, aligning with industry standards for evaluating secondary coolants.

The methodology is structured into four distinct phases:

- 1) Study previous research and design a water-cooled glycol chiller experimental test rig integrated with the required high-precision measuring instruments (flow meters, PT-100 temperature sensors, and power analyzers).
- 2) Prepare different water-ethylene glycol (and optionally propylene glycol) coolant compositions (e.g., 15%, 30%, 45% by volume) and test them under strictly identical operating conditions to isolate the effects of thermophysical property changes.
- 3) Record continuous data for inlet/outlet temperatures, volumetric flow rate, and compressor/pump power consumption. Use these empirical data arrays to calculate the heat rejection rate, temperature drop (ΔT), cycle Coefficient of Performance (COP), and system COP.
- 4) Compare the experimental results computationally and graphically to determine the optimum water-glycol composition that offers the maximum thermal performance without violating the boundary constraints for freeze and corrosion protection.

IV. SCOPE OF THE WORK

The extent encompasses a thorough review of existing literature describing additional coolant attributes, pumping penalties, and advanced optimization procedures. It includes the physical construction or algebraic modeling of a water-cooled chiller apparatus capable of handling sub-zero fluids. The logical extent extends to assessing the non-linear deterioration of the overall heat transfer coefficient (U) as glycol concentrations increase, mapping the resultant expansion of evaporator approach temperatures. Finally, the range entails formulating precise recommendations for HVAC engineers and plant operators regarding the precise dosing of antifreeze to prevent disastrous over-concentration, which would otherwise induce serious parasitic energy losses.

Predicted System Performance Penalty (Relative to Water)

Glycol Type	Concentration	Pump Power Rise	System COP Drop
Ethylene Glycol	15%	+21%	-3.9%
Ethylene Glycol	30%	+56%	-9.1%
Propylene Glycol	30%	+89%	-12.0%
Propylene Glycol	45%	+190%	-20.0%

Table 1: Simulated penalties based on thermophysical deviations.

V. CONCLUSION

While essential for preventing freezing in low-temperature chillers, glycol mixtures introduce significant

thermodynamic and hydraulic penalties, including increased pumping power and reduced thermal conductivity. Propylene Glycol specifically incurs a higher energy penalty than Ethylene Glycol at equivalent concentrations.

To offset these limitations, the industry is adopting ternary salt-glycol formulations, nanoparticle dispersions, and AI-driven control strategies like MI-DPC to maintain peak efficiency. Ultimately, operators must determine the precise, minimum-viable glycol concentration for their specific process, as over-concentrating the fluid causes severe and continuous electrical waste throughout the chiller's lifecycle.

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