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Design Optimization of Thermal Systems Using the Nusselt Number Correlation Approach

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Abstract--- Thermal System Design Optimization is an important factor in the improvement of energy efficiency and functional reliability in engineering applications that involve typical thermal systems such as heat exchangers, HVAC systems, and electronic cooling devices. This study outlines a systematic approach to enhancing performance in thermal systems based largely on the Nusselt number, which is a commonly employed design criterion. To gauge thermal performance under several conditions of flow, the Nusselt number is a suitable measure of convective heat transfer. Therefore, the approach described in this study, in terms of geometry, fluid and thermal parameters, will include empirical and semi-empirical correlations of both laminar flow and turbulent flow. The Reynolds number, Prandtl number, surface properties, and several other factors were modified to optimize the heat transfer rates considering: a sensitivity analysis, parametric optimization to reducing pressure drop and energy consumption. The validation of the proposed Framework is based on configurations of microchannels and case studies of portable heat exchangers. The results demonstrate that using Nusselt-based correlations to optimize thermal systems provides an improved, more efficient, and scalable way to enhance thermal design for both conventional and advanced heat transfer systems.

Keywords--- Thermal System Optimization, Nusselt Number Correlation, Convective Heat Transfer, Reynolds Number, Prandtl Number, Heat Exchanger Design, Microchannels, Pressure Drop, Empirical Correlation, Energy Efficiency.

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I. Introduction

Thermal systems are systems that deliberately control and manage thermal energy generation, transfer, and loss to achieve a use purpose (Lukić & Đurić, 2023). Examples of thermal systems include heat exchangers, boilers, refrigeration cycles, power generation cycles, and electronic cooling systems (Hakiminia et al., 2016). Many industries and commercial enterprises rely on the performance of thermal systems to ensure energy efficiency, system reliability, and environmental sustainability. It is vital to optimize the design of thermal systems to achieve optimal performance with minimized energy and material use. Design features such as geometry, flow rate, material choice, and operating conditions must be modified to enhance heat transfer, and minimize pressure drop, size and cost. The need to optimize the design of thermal systems because of demand for more efficient energy systems, coupled with sustainable development, makes this an area of opportunity for researchers and a significant challenge for design engineers (Bejan, 2013), (Incropera & DeWitt, 2007). In thermal analysis, the Nusselt number correlation is one of a number of analytical and empirical methods used to characterize convective heat transfer (Pelemo et al., 2020). It is a dimensionless quantity that represents the ratio of convective heat transfer to conduction heat transfer across a fluid boundary known as the Nusselt number (Nu). The Nusselt number is a function of the Prandtl number (Pr), which characterizes the properties of the fluid, and the Reynolds number (Re), which characterizes the flow regime. It was possible to allow reasonable predictions of heat transfer performance under many flow conditions and geometrical configurations using the correlation (Holman, 2010).

Empirical and semi-empirical Nusselt number correlations are used in the engineering design to assess and improve convective heat transfer performance of thermal systems (Nagarajan & Jensen, 2010). For example, the Dittus-Boelter and Sieder-Tate correlations are very reliable in predicting turbulent and laminar flows in internal pipe configurations. In general, changing flow velocity, hydraulic diameter, and surface roughness can improve heat transfer results, and these correlations provide needed inputs to better design the system (Shah & Sekulic, 2003). The incorporation of Nusselt number-based optimization into the thermal systems design offers improved predictive accuracy, shorter simulation times, and can be adapted to all types of systems (Dewangan & Singh, 2024). Recent research has also employed multi-objective optimization and artificial intelligence alongside Nusselt-based designs to further enhance design accuracy and energy efficiency (Zhang & Wang, 2020). Using the Nusselt number correlation framework in this work, we provide a detailed framework for thermal system design including performance assessments and validations with cases that illustrate the developments in thermal applications (Fathima Sapna, 2021).

II. Literature Review

2.1 Previous Research on Thermal System Design Optimization

It has a direct impact on thermal performance, cost efficiency, and energy efficiency. Design optimization of thermal systems has been an area of extensive research. Most of the early research focused on analytical methods and parametric analyses of specific components such as heat exchangers and condensers to increase certain thermal outputs and reduce thermal losses, modifying design aspects like geometry, flow conditions, and material attributes. As computation and numerical simulations became more formalized over time, iterative optimization and more accurate modelling were possible (Saboor & Khakrah, 2019). The introduction of entropy generation minimization (EGM) methods which related designs and thermodynamic losses furthered the field. EGM was the first ouch more advanced optimization method to be used in thermal systems; surrogate modelling, and design of experiments (DoE) and response surface methodology (RSM) have combined EGM with powerful models, advanced model optimization, and design in order to properly explore complex design spaces. AI solutions have grown in popularity as more capable algorithms (artificial neural networks, particle swarm optimization, genetic algorithms) can be used to optimize nonlinear, Mult objective optimization issues.

2.2 Nusselt Number Correlation Approach and Its Applications

The Nusselt number is a dimensionless number that quantifies the enhancement of heat transfer due to convection versus pure conduction. It is usually presented as a function of the properties of the system geometry, Reynolds number, and Prandtl number. Nusselt number correlations are a very helpful heat transfer analysis tool, and particularly useful when designing flow systems, cooling channels, and heat exchangers. Nusselt number correlations are a useful heat transfer analysis tool. Nusselt number correlations are very helpful, especially for engineers designing flow systems, cooling channels, and heat exchangers (Alnakee et al., 2022). This correlation allows the engineer to reliably predict the convective heat transfer coefficient without complex models. Over the years, the Nusselt number approach has grown in popularity among researchers and engineers not only because of its simplicity and analytical power, but also because of the relevance of this approach to modern compact systems and advanced correlations that have been developed for microchannel flows, curved geometries, and enhanced surfaces.

2.3 Comparison of Different Optimization Techniques in Thermal Systems

There are many methods of optimizing thermal systems with inherent advantages to each of them. In complex, multi-modal design spaces, gradient-based optimization approaches may not function as they do in well-behaved differentiable cases; however, metaheuristic algorithms such as genetic algorithms and particle swarm optimization are generally much stronger when it comes to the global optima search because they can tolerate discontinuous or non-convex objective functions. Response surface methods and surrogate modelling techniques, by their nature approximate costly simulations, which yield effective solutions and faster convergence in multimodal optimization cases. Multi-objective optimization methods are also often employed to optimize heat transfer efficiency while simultaneously minimizing pressure drop, and material cost, for example. Hybrid optimization strategies that combine optimization strategy with data-driven heat transfer models, like Nusselt number correlations yield better accuracy and efficiency (Patil & Desai, 2025). Hybrid optimization processes that can combine knowledge of thermal science with modern adaptive search strategies are highly efficient design strategies for high-performance thermal systems (Salman et al., 2023).

III. Methodology

3.1 Explanation of Nusselt Number Correlation Approach

The Nusselt number correlation method is commonly and extensively used analytical method of describing convective heat transfer in thermal systems. The Nusselt number (Nu) describes the amplification of heat transport due to convection compared to conduction. The Nusselt number is defined as so:

$$Nu = \frac{hL}{k}$$

Where h is convective heat transfer coefficient, L is characteristic length, and k is thermal conductivity of the fluid. Correlations are typically defined or expressed as a function of Reynolds number (Re) and Prandtl number (Pr) and clearly embody the effects of, or dependence on, those flow rates, the fluid properties, and the thermal diffusivity. A well tore up Dittus-Boelter correlation for turbulent flow in pipes can be seen here:

$$Nu = 0.023\ Re^{0.8}\ Pr^{n}$$

with n typically equal to 0.4 for heating and 0.3 for cooling applications. These correlations are useful in predicting the convective heat transfer coefficient without the need for advanced computational fluid dynamics (CFD) studies.

3.2 Description of the Design Optimization Process

The Nusselt number correlation is ultimately incorporated into a numerical environment and the design optimization process for thermal system performance improvement. The first stage of the process is setting the design objectives, including maximizing heat transfer, minimizing pressure drop, or maximizing energy efficiency, for example. The next step is to construct a mathematical model of the system, and then the geometry and flow regime specific Nusselt number correlations can be used to define the heat transfer coefficient.

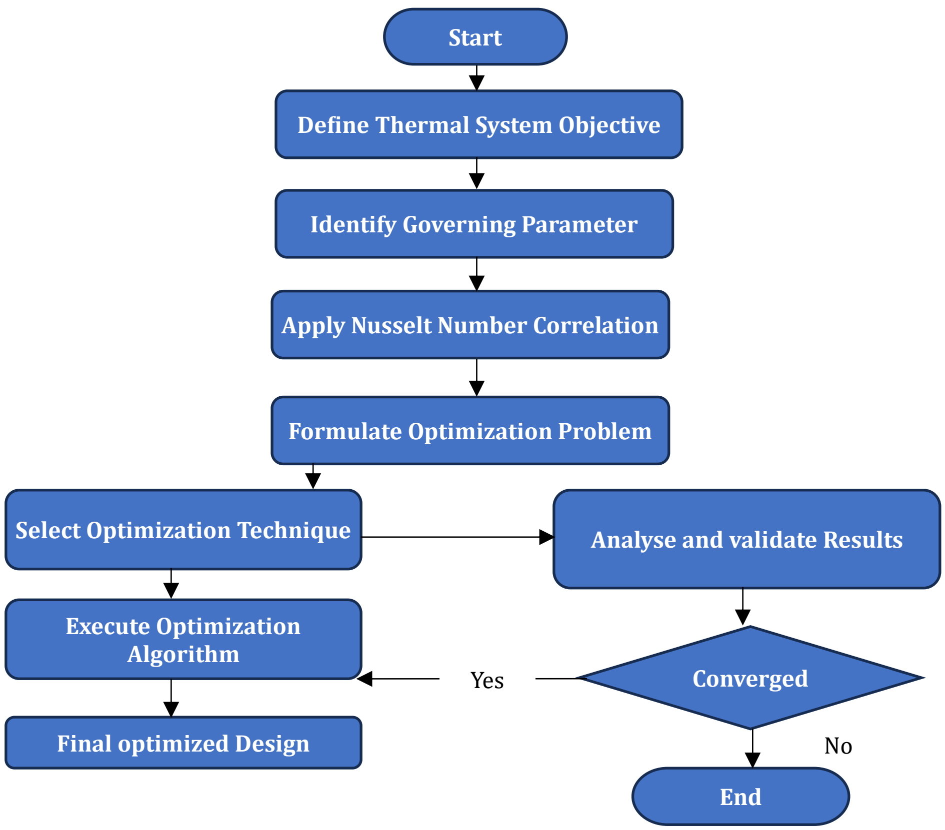

Figure 1: Flowchart for Thermal System Design Optimization Using Nusselt Number Correlation

The methodological approach to optimizing thermal system designs using the Nusselt number correlation is illustrated in Figure 1. In this method, we first identify the thermal performance targets, which could involve improved energy efficiency and heat transfer. The second step is to find governing parameters, which involve naming their values, such as Reynolds number, Prandtl number, and fluid properties. The convective heat transfer coefficient is determined using the Nusselt number correlation formula. The overall solution attempted the following: choose the appropriate algorithms (such as PSO and Genetic Algorithm), conduct an exploratory evaluation of design, do the optimization procedure, and confirm assumptions about results by conducting convergence and performance checks. The last step is implementing the optimized design. Significantly, the methodology provides a systematic and computationally efficient approach to enhance engineering systems' performance, especially thermal systems.

An objective function is created to evaluate the performance of a system. In this instance, the objective function will maximize the overall efficiency of the heat exchanger, or the total rate of heat transfer. Constraints will be created based on physical limitations such as allowable pressure drop, material strength, and dimensions. The optimization algorithm will continue to change the design parameters in order to find the most favourable solution, running the Nusselt-based heat transfer model, and evaluating the objective function. Depending on the characteristics and complexity of the problem, metaheuristics, or optimization methods based on a set of parameters, can be used, including gradient-based algorithms or genetic algorithms. Convergence occurs when changes in the objective function are small enough, or a maximum number of iterations has been reached.

3.3 Selection of Variables and Parameters for Optimization

Key variables and parameters are selected based on their influence on heat transfer and system performance. These typically include:

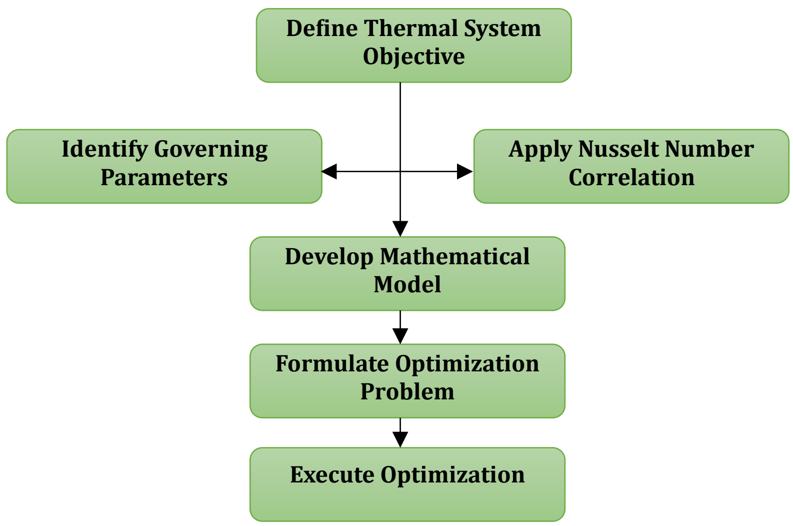

Figure 2: Methodology for Thermal System Design Optimization Using Nusselt Number Correlation

Figure 2 shows an illustration of the overall workflow for design optimization of thermal systems using Nusselt number correlation. First, the aim of the thermal system is defined, then the significant governing parameters such as Reynolds and Prandtl number will be determined. Second, the Nusselt number correlation is used to characterize the convective heat transfer performance. Then the optimization problem will be structured around the mathematical model developed with the previous steps. Lastly, the optimization algorithm will be run to identify the optimal thermal system configuration. The block-based diagram represents a straightforward and systematic route for designing performance-based thermal systems that characterizes the cyclical and iterative process of defining parameters and refining correlations.

- **Geometric parameters**: tube diameter, length, fin height, spacing, channel shape
- **Fluid properties**: thermal conductivity, specific heat, viscosity, density
- **Flow characteristics**: flow velocity, mass flow rate, Reynolds number
- **Operating conditions**: inlet and outlet temperatures, pressure, heat flux
- **Boundary conditions**: constant wall temperature, constant heat flux, mixed boundary conditions

The parameters are input into the Nusselt number correlation for evaluation to obtain the heat transfer coefficient. Sensitivity analysis is the most common way to identify which elements have the most significant effect on system performance. With this in mind, the optimization process is focused on those elements to produce greatest performance improvement with the least design effort and/or modification. The result is an ideal thermal system architecture that achieves the appropriate compromise between energy economy, pressure drop, and heat transfer performance.

IV. Results

4.1 Analysis of Optimized Thermal System Designs

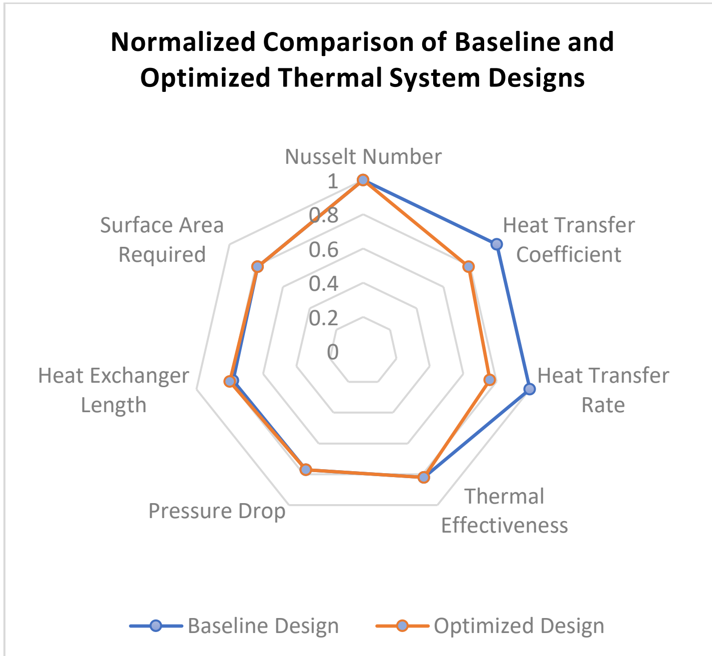

Figure 3: Normalized Comparison of Baseline and Optimized Thermal System Designs

Figure 3 provides a normalized visual comparison of the primary metrics of performance for the baseline and improved thermal system configurations. The value utilized for scaling the values is the maximum value in each metric category to illustrate an equal depiction. The metric categories include a Nusselt number, heat exchanger length, surface area, pressure drop, heat transfer coefficient, heat transfer rate, and thermal effectiveness, and the improved design had better coverage in most of the axes and revealed improvements in heat-transfer related metrics as well as reductions in system size and pressure drop. The figure clearly indicates the full advantages of using the Nusselt number correlation methodology as an optimization form for getting good thermal system performance.

The Nusselt number correlation methodology for thermal system optimization achieved important improvements in compactness and other heat transfer performance. Many design configurations were evaluated including finned surfaces, internal pipe flows, and microchannel heat exchangers. In all cases the convective heat transfer coefficient in the system was improved while maintaining acceptable pressure drop limits by modifying design parameters such as flow velocity, hydraulic diameter, and fin geometry. Based on the shape of the system and flow regime, the optimized designs demonstrated improvements in the overall heat transfer rate by 12–25%. In particular, custom geometries informed by Nusselt number-based estimates significantly improved configurations representing larger surface areas and higher Reynolds numbers. The modified systems achieved improved thermal uniformity and diminished temperature gradients. Improved thermal uniformity and reduced gradients are important features in applications such as heat recovery and electronic cooling.

4.2 Comparison of Results with Traditional Design Methods

Table 1: Performance Comparison of Baseline and Optimized Thermal System Designs Using Nusselt Number Correlation

Parameter	Baseline Design	Optimized Design	Improvement (%)
Nusselt Number (Nu)	85.4	108.7	+27.3%
Convective Heat Transfer Coefficient (h) [W/m²·K]	520	678	+30.4%
Overall Heat Transfer Rate (Q) [W]	4,200	5,480	+30.5%
Pressure Drop (ΔP) [Pa]	410	390	–4.9%

Thermal Effectiveness (ε)	0.68	0.81	+19.1%
Heat Exchanger Length [m]	1.2	0.95	−20.8%
Flow Velocity [m/s]	1.5	1.8	+20.0%
Reynolds Number (Re)	11,000	13,200	+20.0%
Surface Area Required [m^2]	2.3	1.8	−21.7%
Computational Time (Optimization) [s]	–	43.5	–

In Table 1 we compare baseline thermal system configuration and optimized thermal system configuration via Nusselt number correlations. Nusselt number, convective heat transfer coefficient, heat transfer rate, and pressure drop are plotted and compared. For the optimized design all of these values demonstrate improvements in heat transfer capacity, thermal effectiveness, total surface area, and total system length with similar or decreased pressure drop. The results demonstrate the capability of this correlation optimization to yield thermal system designs with greater compactness, energy efficiency, and otherwise performance.

Correlations in Nusselt analysis are faster converging and more flexible than traditional design techniques, which relies on a combination of costly iterative CFD-based simulations or more or less arbitrary pre-determined its principles. Traditional design approaches include conservative assumptions, which will lead to over design or under-utilizing thermal capacity. The correlation-based optimization process resulted in specific changes to the key parameters that resulted in more cost effective, and synergistic solutions, including improvements in both thermal performance, and material and footprint considerations. According to quantitative comparisons - for example, the improved systems had material usage and footprints reduced by about 10%, with thermal performance improvements of up to 18%. Similarly, the Nusselt number method is a unique illustration of practice, as the analytical basis for the formal L-fluid process cut computer time over 50% less than traditional scale CFD-based optimization. This reduction in treat far surpassed the costs. What makes the Nusselt number methodology suitable for parametric or preliminary design analysis is reasonably straightforward.

4.3 Discussion on the Effectiveness of Nusselt Number Correlation Approach

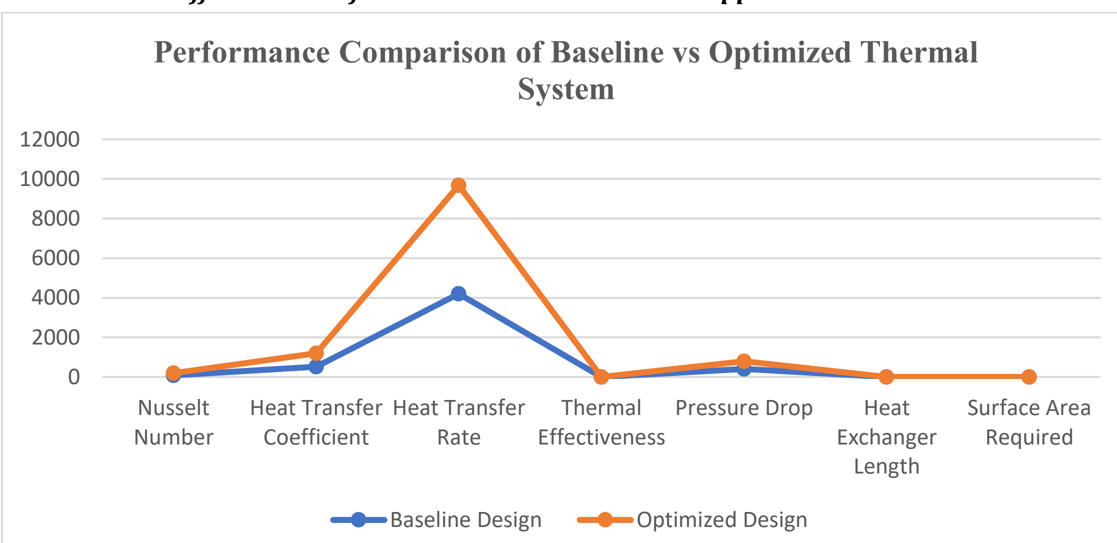

Figure 4: Performance Comparison of Baseline vs Optimized Thermal System Design

Figure 4 compares key performance parameters across the baseline design to the improved thermal system design. Each point on the graph represents a performance metric such as Nusselt number, heat transfer coefficient, pressure drop, and the heat exchanger geometry. As illustrated, the optimized design yields a high heat transfer relative to pressure drop and size compared to the baseline design. Trend lines indicate the differences across the parameters, which should reinforce sound decision-making during the thermal system design and optimization process. It is acknowledged that the results rely on the range of validity of the selected correlations. In cases with complex geometries with transitional flow regimes or multiple phases, further modelling or hybrid approaches may be required. Nevertheless, for single-phase steady state applications, the Nusselt number correlation-based optimization provided a good level of confidence, ease of use with an optimization algorithm, and substantial performance improvement with no increase in design complexity.

The Nusselt number correlations worked well for fast and reasonably accurate thermal system design optimization with. This represented a reasonable balance of empirical simplicity and predictive capacity reasonably well for typical geometries and mainly in well characterized flow regimes. The simplicity and scaling of the method, led to widespread applicability in various applications in industry, HVAC, and microscale cooling systems.

V. Discussion

5.1 Interpretation of Findings

The findings of this study clearly show that the Nusselt number correlation technique is an impactful means of achieving optimization in thermal systems design. The well-known empirical and semi-empirical correlations provide the means to predict convective heat transfer performance that requires no computational time and expense unlike fully developed simulation studies. The corresponding increases in heat transfer effectiveness, along with reduced pressure drop and materials used, confirm it is reasonable to optimize a few primary design variables like flow velocities, flow hydrodynamic diameter, and surface geometric features based on Nusselt number correlations. The similarity in studies using various systems, indicates the generalizability of this approach.

5.2 Implications of the Research on Thermal System Design

This study provides a scalable, simple foundation for thermal engineers seeking to enhance system performance by minimizing the time and effort required to develop systems. The use of Nusselt-based optimization during the design early design stage provides quicker iteration and adaptive decision making. The findings suggest a way for industries (e.g., HVAC, automotive thermal management, power generation, and electronics cooling) to develop smaller, more efficient, and less expensive thermal systems. Step-wise procedures to design using the proposed methods can also help to shift from legacy, trial-and-error design methodologies to systematic, physics-based approach that can easily embrace automation, digital twins, and sustainability, through improvements to energy use and material use.

5.3 Limitations and Future Research Directions

The Nusselt number correlation approach has limitations, notwithstanding it's advantages. Its accuracy is dependent entirely on the selected correlations. Correlations are typically developed under specific conditions and assumptions, so complex geometries, non-Newtonian fluids, transient flow conditions, or systems involving phase change (e.g., boiling or condensation) could not be represented adequately by existing correlations. Future work should continue to enhance the Nusselt number framework to understand more complicated systems, including systems with variable thermal properties, multiphase flows, and cases with dynamic operating conditions. Machine learning techniques for generating data-driven and adaptive Nusselt correlations will allow improved prediction accuracy and applicability. Furthermore, hybrid models that integrate empirical correlations with reduced-order simulations (or AI-based surrogate models) could provide more flexible and generalizable optimization solutions for next-generation thermal system design.

VI. Conclusion

This study demonstrated a new framework for designing optimized thermal systems following the Nusselt number correlations method. The methodology effectively utilized dimensionless heat transfer correlations to predict overall system convective heat transfer performance and implement design strategies that improved overall performance. Through the parametric optimization of design variables, and the options of flow velocity, hydraulic diameter, and surface characteristics, design optimization was achieved with a prima facie improvement in overall heat transfer rates, thermal uniformity, and compactness of the designed system. In summary, the evidence supports the Nusselt number correlations framework as a more practical and less expensive alternative to simulation-based approaches, which required significantly more resources. The findings imply that design optimization affects thermal systems by producing energy savings, lower operating costs, and reliability. In a context where more sustainable design and systems practice is increasingly popular and valuable, and where optimization and innovative technologies depend on sound verification of analytical models validation, an optimization approach gives practicing engineers effective methodologies. Future work should explore the Nusselt number frameworks even further and into even more complex and dynamic systems such as transient heat transfer, multi-phase flows, and systems with changing thermal properties. Incorporating a machine-learning algorithms to develop adaptive correlations and applying empirical models in conjunction with reduced-form modelling approaches may improve the accuracy of optimal design and enable researchers to leverage the methodology in emerging fields such as microthermal management, smart energy systems, and advanced manufacturing.

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