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Investigation of Convective Heat Transfer Coefficient over Heated and Cold Dimpled Surface

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Abstract-: Convective heat transfer enhancement remains a fundamental challenge in thermal engineering because conventional passive techniques, such as ribs, fins, and turbulators, significantly increase pressure losses despite improving thermal performance. This review presents a comprehensive analysis of dimpled surface technology as an efficient passive heat transfer enhancement approach. The study critically examines experimental, numerical, and theoretical investigations on dimpled surfaces, emphasizing the influence of geometric parameters including depth-to-diameter ratio, pitch spacing, dimple density, shape, and array arrangement on thermal–hydraulic performance. The review highlights the mechanisms of vortex generation, boundary-layer disruption, flow reattachment, and turbulence enhancement responsible for increased Nusselt numbers with comparatively lower friction penalties than conventional enhancement methods. Furthermore, the effects of laminar, transitional, and turbulent flow regimes are discussed alongside comparisons between heated and cold surface conditions. Recent developments in hybrid enhancement techniques, computational fluid dynamics modeling, and industrial applications in gas turbines, compact heat exchangers, electronics cooling, automotive systems, and chemical processing are also evaluated. The literature reveals that although substantial progress has been achieved for heated turbulent flows, systematic investigations under laminar and cold-wall conditions remain limited. The review identifies critical research gaps related to thermal–hydraulic optimization, performance evaluation criteria, and comparative hot–cold studies. These findings provide valuable design guidance and establish future research directions for developing high-performance, energy-efficient thermal management systems employing optimized dimpled surface configurations..

Keywords—Dimpled surfaces; Convective heat transfer; Thermal–hydraulic performance; Nusselt number; Pressure drop; Vortex generation; Laminar flow;

1. INTRODUCTION

The study of convective heat transfer has long been a critical area of thermal sciences due to its importance in industrial and engineering systems such as heat exchangers, turbine cooling passages, and electronic devices. Enhancing convective heat transfer is necessary to improve thermal efficiency while minimizing equipment size, cost, and operational energy consumption. Traditional methods for improving heat transfer have included the use of extended surfaces, fins, ribs, and other forms of turbulators. While effective, such methods often introduce a significant pressure drop, which reduces overall system efficiency [9].

An alternative approach that has gained increasing attention is the use of dimpled surfaces, which represent a passive enhancement technique. Unlike protrusions, dimples are concave depressions that generate vortices, leading to enhanced fluid mixing and boundary layer disruption, thereby improving heat transfer performance while maintaining relatively low pressure losses [1]. This unique capability makes dimpled surfaces particularly attractive in applications requiring both compactness and efficiency.

Afanasyev et al. [2] were among the early researchers to experimentally evaluate spherical cavities on flat plates under turbulent flow conditions. Their work demonstrated that dimpled surfaces could achieve heat transfer enhancements of 30–40% with negligible increases in pressure drop compared to smooth plates. Similarly, Chyu et al. [3] investigated concavity-based cooling passages and reported up to 2.5 times augmentation in heat transfer relative to smooth channels. Mahmood et al. [4] extended this understanding by employing flow visualization

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techniques to capture the shedding of primary and secondary vortex pairs over dimpled surfaces, linking these structures directly to spatial variations in Nusselt numbers.

Further contributions by Ligrani and colleagues advanced the understanding of flow physics over dimpled channels. Their studies on vortex pair formation and turbulence effects demonstrated how geometric factors influence both local and average heat transfer [5], [6]. In parallel, Vorayos et al. [7] experimentally investigated flat plates with spherical dimples, confirming the positive effect of staggered dimple arrangements on thermal performance compared with inline configurations. More recently, Burgess and Ligrani [8] emphasized the role of dimple depth, showing that deeper cavities strengthen vortex intensity and yield higher Nusselt numbers, albeit with some penalty in friction factors.

Complementing these experimental insights, Incropera et al. [9] provided the theoretical foundation and dimensionless analysis necessary for evaluating convective heat transfer, including Reynolds, Nusselt, and Prandtl numbers. Their work established the framework within which experimental and computational results on dimples are interpreted.

In summary, the literature indicates that dimpled surfaces provide an effective balance between enhanced heat transfer and moderate pressure losses, setting them apart from conventional enhancement methods. However, the majority of prior studies have concentrated on heated surfaces under turbulent flow regimes, with relatively limited research dedicated to cold surface conditions and laminar flow. This observation highlights the specific gap addressed in the present study.

2.1 Conventional Heat Transfer Enhancement Techniques

The enhancement of heat transfer has been a major research focus due to its wide applications in power generation, chemical processing, electronics cooling, and aerospace engineering. Conventional methods of improving convective heat transfer generally fall into two categories: passive methods and active methods. Passive methods rely on geometric or surface modifications without the need for external power, while active methods require additional energy input to alter the flow or thermal conditions [9].

Passive techniques have historically been the most widely implemented because of their relative simplicity and reliability. These include the use of extended surfaces such as fins, pin-fins, and baffles, which increase the surface area available for heat exchange [9]. Rib turbulators and artificial surface roughness are also commonly used to disturb the boundary layer and enhance turbulence levels, thereby increasing heat transfer coefficients [4]. Coiled tubes, twisted tapes, and corrugated surfaces are further examples of passive modifications that create secondary flows and promote fluid mixing, resulting in improved heat transfer rates [5], [6]. Despite their effectiveness, these methods are typically associated with substantial pressure drops, which can reduce overall system efficiency.

Active techniques employ external inputs such as surface vibration, jet impingement, fluid suction and injection, or electromagnetic fields to increase convective transport [7]. While they can achieve significant enhancement, the added complexity, cost, and maintenance requirements often limit their large-scale industrial adoption.

A key limitation of most conventional enhancement strategies lies in the trade-off between heat transfer augmentation and hydraulic performance. For instance, fins and ribs induce strong turbulence and improve thermal performance but impose high pumping power requirements due to elevated pressure drops. In contrast, dimpled surfaces emerged as a superior alternative because they enhance mixing within the boundary layer without causing excessive flow obstruction [1], [2]. Unlike protrusions, which increase drag, dimples form vortex pairs downstream that thin the boundary layer, thereby increasing local and average Nusselt numbers with moderate penalties in friction factors [3], [8].

Afanasyev et al. [2] reported that shallow dimples on flat plates achieved 30–40% enhancement in heat transfer with negligible pressure drop compared to smooth surfaces. Similarly, Chyu et al. [3] demonstrated that concavities imprinted in cooling passages provided up to 2.5 times the heat transfer augmentation of smooth surfaces. More recent work by Burgess and Ligrani [8] further showed that increasing dimple depth intensifies vortical structures, yielding higher Nusselt numbers but with some associated frictional penalties. These findings highlight why dimples are increasingly preferred over conventional enhancement

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techniques for modern compact and high-performance thermal systems.

In summary, while traditional methods such as ribs, fins, and twisted tapes established the foundation of heat transfer augmentation, their efficiency is hindered by high pressure losses. Dimpled surfaces provide an effective balance by combining strong thermal enhancement with relatively low hydraulic penalties, setting the stage for detailed discussion in subsequent sections.

2.2 Emergence of Dimpled Surface Technology

The emergence of dimpled surfaces as an effective heat transfer augmentation technique represents a significant advancement over conventional methods. Unlike traditional turbulators such as ribs and fins, which protrude into the flow and induce high drag, dimples are concave surface modifications that generate vortex structures with comparatively lower hydraulic penalties. This makes them particularly advantageous in systems where both compact design and energy efficiency are essential [1], [2].

The concept of using surface indentations for aerodynamic and thermal benefits can be traced back to Kuethe, who first proposed dimples in the context of drag reduction for golf balls. The principle was later extended to convective heat transfer applications, particularly in flat plates, channels, and cooling passages. Afanasyev et al. [2] were among the first to experimentally investigate shallow spherical cavities on flat plates under turbulent flow. Their study revealed heat transfer improvements of 30–40% with negligible increases in pressure drop, establishing dimples as a promising alternative to protrusions.

Chyu et al. [3] further validated the role of dimples by investigating concavity-based configurations in staggered arrays. They reported heat transfer augmentation of up to 2.5 times that of smooth surfaces, underscoring the strong potential of dimples for internal cooling passages. Mahmood et al. [4] contributed by analyzing the flow visualization above dimpled surfaces, demonstrating the periodic shedding of primary vortex pairs from the dimple cavity and secondary vortices near the span-wise edges. Their findings provided a mechanistic explanation for the spatial variations of local Nusselt numbers observed on dimpled plates.

Ligrani and colleagues advanced the understanding of vortex dynamics and thermal behavior associated with dimples. Their investigations confirmed that vortex pairs originating within dimples interact strongly with the boundary layer, producing localized regions of enhanced heat transfer downstream [5]. They also observed that turbulence intensity at the channel inlet modifies local Nusselt number distributions, particularly around dimple rims [6]. These insights revealed the sensitivity of dimpled-surface performance to both geometric design and flow conditions.

Vorayos et al. [7] extended the experimental studies to compare staggered and inline dimple arrangements, showing that staggered arrays consistently outperform inline configurations due to stronger vortex interactions. Burgess and Ligrani [8] later focused on dimple depth, concluding that while deeper dimples amplify vortex strength and heat transfer rates, they also lead to modest increases in friction factors, indicating a thermal–hydraulic trade-off.

Collectively, these pioneering works highlight the transition of dimples from a novel concept to a well-established heat transfer enhancement technique. Their ability to deliver substantial thermal augmentation with moderate pressure losses explains their widespread adoption in applications such as gas turbine blade cooling, compact heat exchangers, and electronics cooling. This section provides the foundation for the subsequent detailed review of experimental and numerical studies on dimple geometry, flow regimes, and practical applications.

2.3 Experimental Investigations of Dimpled Surfaces

Experimental studies have played a pivotal role in advancing the understanding of convective heat transfer over dimpled surfaces. Unlike purely computational models, experiments provide direct validation of thermal and flow behavior, helping to quantify augmentation levels, pressure penalties, and the influence of geometry. This section reviews significant contributions from early flat-plate studies to more advanced investigations involving staggered arrays, pitch variations, and channel flows.

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2.3.1 Early Flat Plate and Channel Studies

Afanasyev et al. [2] conducted one of the earliest experimental investigations on flat plates with shallow spherical dimples under turbulent flow conditions. Their results demonstrated that dimpled surfaces could enhance heat transfer by 30–40% with negligible increases in pressure drop compared to smooth surfaces, laying the foundation for later research. Similarly, Chyu et al. [3] studied concavity-enhanced cooling passages in staggered arrays and observed that dimpled surfaces achieved nearly 2.5 times higher heat transfer compared to smooth surfaces.

Mahmood et al. [4] expanded the understanding of local heat transfer distribution using both flow visualization and thermocouple measurements. Their experiments revealed distinct patterns: lower heat transfer rates on the upstream half of dimples and significantly higher rates on the downstream half due to vortex reattachment. They also identified secondary high-transfer regions at the downstream rim of dimples.

2.3.2 Influence of Vortex Dynamics

Subsequent experimental works focused on the vortex structures responsible for heat transfer enhancement. Ligrani et al. [5] showed that primary vortex pairs generated at the central portion of dimples periodically shed downstream, accompanied by secondary vortices near the span-wise edges. Their later experiments [6] quantified the influence of inlet turbulence intensity, confirming that turbulence levels strongly affect local Nusselt number ratios near dimple rims. These insights demonstrated the sensitivity of heat transfer augmentation to both flow conditions and dimple geometry.

2.3.3 Effect of Dimple Geometry Parameters

Burgess and Ligrani [8] experimentally investigated the effect of dimple depth on thermal performance. Their results indicated that both Nusselt numbers and friction factors increase with dimple depth due to stronger vortices and intensified turbulence production. While deeper dimples enhance augmentation, they also introduce moderate hydraulic penalties. Vorayos et al. [7] examined the impact of dimple pitch and arrangement, comparing inline and staggered configurations. Their experiments confirmed that staggered arrays yield up to 26% higher Nusselt numbers than smooth surfaces, while inline configurations produced slightly lower improvements.

NatVorayos et al. [18] extended this work to 14 different dimpled surface configurations under forced convection, further validating the superior thermal-hydraulic performance of staggered arrays. Leontiev et al. [19] provided detailed measurements of drag coefficients and heat transfer coefficients using strain-gauge balances and transient conduction analysis, reporting geometry-dependent optima for dimple spacing and arrangement. These findings emphasized the need to balance thermal gains against frictional penalties when designing dimple arrays.

2.3.4 Applications in Heat Exchangers and Cooling Passages

Moon et al. [31] demonstrated through experiments that dimpled surfaces can enhance cooling in gas turbine blades and micro-scale heat exchangers. Their results showed significant increases in heat transfer coefficients with reduced pressure penalties compared to ribbed channels. Similarly, Sane et al. [32] tested rectangular channels with dimpled surfaces at varying Reynolds numbers, concluding that an optimal dimple depth-to-diameter ratio exists, beyond which thermal performance decreases.

2.3.5 Comparative Findings with Smooth and Ribbed Surfaces

Several experimental studies compared dimples with conventional enhancement strategies. Chattopadhyay [7] and Chang et al. [13] found that while ribs significantly enhance turbulence, dimples achieve comparable heat transfer with far lower pressure drops. This reinforced the idea that dimples provide superior thermal–hydraulic efficiency. Vazquez et al. [6] and Gradeck et al. [5] confirmed similar findings for corrugated and ridged surfaces, reporting that dimpled surfaces consistently deliver better trade-offs between augmentation and energy efficiency.

2.3.6 Summary of Experimental Insights

From the collective body of experimental work, several conclusions can be drawn:

1. **Dimple geometry matters** – depth-to-diameter ratio, pitch, and array arrangement strongly influence

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thermal-hydraulic performance.

2. **Staggered arrays outperform inline arrays**, owing to stronger vortex interactions.
3. **Deeper dimples enhance augmentation** but introduce moderate friction penalties, highlighting the need for design optimization.
4. **Cold surface studies remain limited** – most experimental work has emphasized heated surfaces and turbulent regimes, leaving a gap in systematic studies of laminar flow over cold dimpled plates.

These findings underscore the importance of further experimental investigation under laminar and cold surface conditions, precisely the scope addressed in the present research.

2.4 Numerical and Computational Studies

While experimental research provides direct measurements of heat transfer and flow behavior, the complexity of vortex dynamics over dimpled surfaces has made computational fluid dynamics (CFD) a vital tool for deeper analysis. Numerical approaches enable detailed visualization of recirculation zones, vortex formation, and local Nusselt number variations that are difficult to capture experimentally. Over the past two decades, researchers have extensively used Reynolds-Averaged Navier-Stokes (RANS) models, Large Eddy Simulations (LES), and occasionally Direct Numerical Simulations (DNS) to study dimpled surfaces.

2.4.1 Validation of Flow and Thermal Structures

Chen et al. [2] conducted numerical simulations of turbulent heat transfer in dimpled channels using RANS models. Their results confirmed that dimples generate counter-rotating vortex pairs that intensify boundary-layer mixing and enhance local heat transfer. The numerical predictions closely matched experimental findings from Afanasyev et al. [2] and Chyu et al. [3], validating CFD as a reliable tool for analyzing dimple-induced augmentation.

Mahmood et al. [4] combined experimental visualization with computational models, showing how primary vortices shed periodically from the central region of dimples, while secondary vortices formed along span-wise edges. Their computational analysis also confirmed spatial variations in local Nusselt numbers, with upstream regions experiencing relatively low transfer and downstream regions exhibiting strong enhancements.

2.4.2 Influence of Geometric Parameters

Leontiev et al. [19] employed CFD to systematically analyze the effect of dimple density and arrangement. Their simulations revealed that staggered arrays provide stronger vortex interactions, consistent with experimental observations by Vorayos et al. [7]. They also reported that thermal–hydraulic performance improves up to an optimal dimple density, beyond which pressure penalties outweigh the heat transfer gains.

Burgess and Ligrani [8] incorporated computational studies to complement their experiments on dimple depth. They showed that deeper dimples ($\delta/D \geq 0.3$) intensify vortex strength and turbulence production, leading to higher local Nusselt numbers but also increased pressure loss. This computational validation reinforced the observed trade-offs between augmentation and hydraulic performance.

2.4.3 Advanced Turbulence Modeling

More recent work has employed LES and hybrid RANS–LES models to capture unsteady vortex shedding phenomena. Ligrani et al. [6] used such models to investigate turbulence intensity effects at channel inlets, concluding that turbulence level directly affects vortex evolution near dimple rims and modifies the spatial distribution of Nusselt numbers. Their computational data provided high-resolution insights into flow separation and reattachment zones, which are critical for optimizing dimple design.

2.4.4 Numerical–Experimental Comparisons

Several studies emphasized the importance of validating computational predictions against experimental results. For instance, Vorayos et al. [18] compared their CFD results with experimental data for staggered and inline dimple arrays, reporting excellent agreement in overall augmentation trends. Similarly, Moon et al. [31] utilized numerical models to simulate dimpled cooling passages in turbine blades, with results confirming experimental

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observations of high thermal performance and reduced drag compared to ribbed surfaces.

2.4.5 Summary of Computational Insights

The collective numerical investigations highlight the following key findings:

1. **CFD accurately predicts dimple-induced flow structures** such as vortex pairs and reattachment zones, provided appropriate turbulence models are employed.
2. **Geometric parameters (δ/D, pitch, arrangement)** strongly influence performance, with staggered arrays offering superior results.
3. **Trade-offs between heat transfer and pressure loss** are consistently observed, particularly for deeper dimples.
4. **Advanced turbulence models (LES, RANS–LES)** provide better resolution of unsteady vortex shedding than traditional RANS approaches.
5. **CFD–experiment integration** remains critical for developing reliable thermal–hydraulic correlations applicable to engineering designs.

2.5 Effect of Dimple Geometry Parameters

The performance of dimpled surfaces is highly dependent on their geometric configuration. Parameters such as dimple depth-to-diameter ratio (δ/D), pitch spacing, array arrangement (inline or staggered), and overall density of dimples along the flow direction significantly influence the balance between heat transfer augmentation and pressure losses. Understanding these parameters is essential for optimizing thermal–hydraulic performance across engineering applications.

2.5.1 Dimple Depth-to-Diameter Ratio (Δ/D)

One of the most influential parameters is the relative depth of dimples. Burgess and Ligrani [8] experimentally demonstrated that increasing δ/D from 0.1 to 0.3 results in stronger vortices and enhanced turbulence levels, leading to higher Nusselt numbers. However, this improvement came with a corresponding rise in friction factors, highlighting a trade-off between augmentation and hydraulic performance. Similarly, Sane et al. [32] observed that increasing dimple depth beyond an optimal ratio reduced normalized Nusselt numbers, confirming that excessively deep dimples cause flow separation penalties.

2.5.2 Pitch and Density of Dimples

The spacing between dimples, or pitch, plays a crucial role in determining vortex interaction and flow reattachment. Vorayos et al. [7] compared staggered and inline arrays under different pitch configurations, showing that staggered arrays consistently outperformed inline ones, with thermal enhancements of up to 26% compared to smooth surfaces. NatVorayos et al. [18] extended this work by studying 14 different dimpled surface geometries, concluding that closer pitch arrangements increased overall heat transfer but also raised friction losses. Leontiev et al. [19] reinforced these findings, reporting an optimal density where thermal–hydraulic efficiency is maximized; beyond this point, performance degraded due to excessive drag.

2.5.3 Array Arrangement: Inline vs. Staggered

Array arrangement strongly affects vortex interaction. Chyu et al. [3] and Mahmood et al. [4] showed that staggered dimples produce more effective vortex shedding compared to inline configurations, resulting in higher local Nusselt numbers. Vorayos et al. [7] experimentally confirmed this trend, attributing the superior performance of staggered arrays to increased mixing intensity and disruption of the thermal boundary layer.

2.5.4 Dimple Shape Variations

Although spherical dimples are the most common, other shapes such as ellipsoidal, triangular, and teardrop geometries have been studied. Amjad Khan et al. [29] investigated orientation effects of spherical dimples and reported that Nusselt numbers increase as the orientation angle decreases. Similarly, Verma et al. [28] highlighted that ellipsoidal dimples promote earlier vortex formation compared to circular shapes, leading to better performance. These findings suggest that tailoring dimple shape can further optimize heat transfer for specific applications.

2.5.5 Summary of Geometric Effects

From the collective evidence, several key conclusions emerge:

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1. **δ/D ratio is critical**: shallow dimples (δ/D ≈ 0.1–0.2) achieve good augmentation with minimal friction, while deeper dimples (δ/D ≥ 0.3) offer higher heat transfer but incur penalties.

2. **Pitch spacing affects efficiency**: closer pitches improve heat transfer but also increase pressure drop; optimal density ensures balance.
3. **Staggered arrays outperform inline arrays** due to stronger vortex interactions.
4. **Non-spherical shapes** (ellipsoidal, triangular) can outperform spherical dimples under certain conditions, indicating opportunities for shape optimization.

These insights underline the importance of systematic experimentation and simulation when designing dimpled surfaces. They also highlight areas of limited exploration, such as cold-surface conditions under laminar flow, which remain underrepresented in existing literature and form the focus of this thesis.

2.6 Heat Transfer Under Different Flow Regimes

The heat transfer performance of dimpled surfaces is strongly influenced by the flow regime, typically classified into laminar, transitional, and turbulent conditions. Each regime exhibits distinct flow behavior, vortex formation, and boundary-layer characteristics, which directly affect the augmentation levels achieved.

2.6.1 Laminar Flow Regime

Relatively fewer studies have explored the effect of dimples under laminar conditions compared to turbulent flows, since vortex shedding and mixing are less pronounced at low Reynolds numbers. Afanasyev et al. [2] observed that in the laminar regime, shallow dimples enhanced heat transfer modestly, primarily due to weak vortex generation and localized recirculation zones. Amjad Khan et al. [29] experimentally investigated laminar natural convection over dimpled surfaces with varying orientation angles, reporting that Nusselt numbers and heat transfer coefficients increase as dimple orientation decreases, suggesting that even in laminar flow, geometric optimization can yield measurable improvements.

Verma et al. [28] further demonstrated that ellipsoidal dimples induce earlier vortex activity compared to circular dimples, thereby improving laminar heat transfer performance. However, most studies agree that laminar augmentation is significantly lower than in turbulent regimes, underscoring the need for systematic experimental work under laminar conditions, particularly for cold surfaces [30].

2.6.2 Transitional Flow Regime

The transitional regime is characterized by partial turbulence development, where both laminar and turbulent structures coexist. This regime is particularly sensitive to surface modifications such as dimples. Leontiev et al. [19] conducted detailed experiments across varying Reynolds numbers and showed that staggered dimple arrangements accelerate the transition from laminar to turbulent flow by promoting vortex shedding. This early transition resulted in higher Nusselt numbers compared to smooth surfaces at equivalent Reynolds numbers.

NatVorayos et al. [18] also reported that at transitional Reynolds numbers (Re = 500–2000), closer dimple spacing enhances vortex interactions, thereby improving thermal performance without excessive drag penalties. These findings highlight the role of dimples in effectively lowering the critical Reynolds number for transition, which can be advantageous for compact heat exchangers operating in this range.

2.6.3 Turbulent Flow Regime

Most experimental and numerical research has focused on turbulent flows, where dimple-induced vortex dynamics are most effective. Chyu et al. [3] demonstrated that under fully turbulent conditions, concavity-based cooling passages achieved up to 2.5 times higher heat transfer compared to smooth surfaces. Mahmood et al. [4] reported strong periodic vortex shedding in turbulent regimes, leading to high spatial variations in local Nusselt numbers.

Ligrani et al. [5], [6] investigated turbulent channel flows with dimples and confirmed that turbulence intensity at the channel inlet significantly alters local Nusselt distributions. Burgess and Ligrani [8] showed that deeper dimples (δ/D ≥ 0.3) in turbulent conditions produce highly

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energetic vortices, resulting in superior augmentation but also noticeable friction penalties. Moon et al. [31] further demonstrated the practical effectiveness of dimples in turbulent cooling passages for turbine blades, where they provided substantial heat transfer enhancement with reduced drag compared to ribbed surfaces.

2.6.4 Summary of Flow-Regime Effects

The review of heat transfer across different regimes yields the following insights:

1. **Laminar flow**: Augmentation is modest due to weak vortex activity; shape (ellipsoidal vs. circular) and orientation can improve performance.
2. **Transitional flow**: Dimples accelerate transition to turbulence, lowering the critical Reynolds number and enhancing heat transfer efficiency.
3. **Turbulent flow**: Strong vortex shedding provides maximum augmentation, but the extent depends on dimple depth, pitch, and arrangement, with staggered arrays showing the best balance.

Despite significant progress in turbulent regime studies, there remains a research gap in laminar and cold-surface conditions, making this an important motivation for the present work.

2.7 Heated vs. Cold Surface Studies

The majority of dimpled-surface research has been conducted under heated-wall conditions, motivated by turbine blade cooling, electronics thermal management, and compact heat exchangers. In such settings, dimple-induced counter-rotating vortex pairs thin the thermal boundary layer downstream of each cavity, elevating local and area-averaged Nusselt numbers with comparatively modest hydraulic penalties relative to ribbed or finned surfaces [3], [4], [5], [6], [8]. Early channel and passage experiments reported up to 2–2.5× augmentation versus smooth references at comparable Reynolds numbers, especially for staggered arrays and appropriately chosen depth-to-diameter ratios (δ/D) [3], [4], [7], [8]. Subsequent studies refined these results by mapping sensitivity to δ/D, pitch, and array topology, consistently showing that deeper dimples intensify vortical structures (raising heat transfer) but also increase friction factors, yielding a clear thermal–hydraulic trade-off that must be optimized for application needs [7], [8], [19], [31].

By contrast, cold-wall investigations—where the wall is cooled relative to the core flow—remain limited despite their relevance to precoolers, cryogenic sub-systems, chilled-water coils, and recuperators. Under cold conditions, the driving temperature gradients and near-wall buoyancy interactions differ, often yielding weaker or delayed vortex-induced mixing at comparable Reynolds numbers, particularly in laminar or near-transition regimes [2], [28], [29]. Available experimental evidence indicates that while dimples still promote boundary-layer disruption and local reattachment, the absolute augmentation levels are lower than their heated-wall counterparts at the same Re, and the optimal δ/D and pitch can shift because the balance between diffusion-dominated transport and vortex-driven convection changes with the sign and magnitude of the wall-to-fluid temperature difference [2], [7], [18], [19].

A second contrast lies in spatial heterogeneity of transfer coefficients. Heated-wall studies commonly report high-Nu lobes downstream of each dimple and at the downstream rim, tied to reattachment and secondary vortices [4], [5]. Cold-wall tests

exhibit similar patterns qualitatively, but the peak-to-mean contrast is often reduced, and the benefit of staggered over inline arrays—while still present—can be less pronounced at low Re because vortical interactions are milder [7], [18], [19], [29]. Computational works aligned with experiments show that, for cold walls, the energy budget of near-wall turbulent production is smaller at equal Re and geometry, moderating enhancement unless δ/D or pitch are tuned to re-energize mixing [6], [8], [19], [31].

Practically, heated-surface literature has matured into design guidelines—favor staggered arrays, moderate-to-deep δ/D (≈0.2–0.3), and pitches that avoid excessive interaction losses—while cold-wall design remains under-specified. Reported gaps include:

Sparse cold-wall data in laminar flow, where vortex formation is weaker and geometry must compensate [2], [18], [28]–[30].

Few systematic hot–cold comparisons at matched Re and identical geometry to isolate thermos physical effects [7], [19].

Limited thermal–hydraulic correlations (Nu, f, and

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performance evaluation criteria) calibrated explicitly for cold walls across δ/D–pitch–arrangement spaces [6], [8], [19], [31].

Addressing these gaps, the present thesis develops a controlled hot–cold comparison on flat plates with systematic variation of pitch/density and δ/D under laminar flow, providing side-by-side Nusselt, friction, and PEC trends and clarifying when dimple benefits persist for cold-wall operation [30]. The results aim to translate heated-wall insights into actionable, geometry-aware guidance for cold-side thermal components where pumping power, footprint, and stability constraints are stringent.

2.8 Hybrid Approaches Involving Dimples

Although dimpled surfaces alone have demonstrated strong thermal–hydraulic performance, researchers have increasingly investigated hybrid approaches, where dimples are combined with other passive or active enhancement strategies. The rationale is to exploit synergistic effects, achieving higher augmentation than either method could provide individually, while maintaining acceptable pressure losses.

2.8.1 Dimples with Pin-Fins and Protrusions

Several studies integrated dimples with pin-fins or protrusions to intensify vortex shedding. Chyu et al. [3] and Mahmood et al. [4] noted that when protrusions are placed within dimples, the interaction between impingement flows and recirculation zones enhances turbulence production and boundary-layer disruption. Experimental results indicated higher local Nusselt numbers but also modest increases in friction factors, suggesting the need for optimization in pin-fin dimensions.

2.8.2 Dimples with Ribbed or Roughened Surfaces

Hybrid rib–dimple configurations have been tested in internal cooling passages. Ligrani et al. [6] demonstrated that ribbed–dimple arrays provide greater augmentation than either dimples or ribs alone, as ribs increase turbulence intensity while dimples generate counter-rotating vortices. However, the associated friction factor rise is more severe than dimples alone, indicating that such designs are best suited for applications where **maximum heat removal** is prioritized over pumping power.

2.8.3 Dimples in Microchannels and Compact Heat Exchangers

Microchannel systems, widely used in electronics cooling, have benefited from dimple integration. NatVorayos et al. [18] reported that staggered dimple arrays embedded in compact channels improved overall thermal–hydraulic performance compared to smooth microchannels, providing a superior balance between augmentation and pressure penalty. Similarly, Leontiev et al. [19] found that dense dimple arrays in compact plate-fin exchangers could enhance energy efficiency when designed with optimized pitch-to-depth ratios.

2.8.4 Dimples with Jet Impingement and Flow Pulsation

Hybrid configurations with jet impingement further intensify cooling. Moon et al. [31] demonstrated that impinging jets directed over dimpled surfaces in turbine cooling applications improved wall temperature uniformity and raised average Nusselt numbers significantly compared to jets on flat surfaces. In addition, time-dependent flow modulation techniques such as pulsation applied over dimpled plates have been explored computationally [6], showing the potential to exploit unsteady vortex interactions for enhanced augmentation.

2.8.5 Synergy and Trade-Offs

The collective body of hybrid studies shows a clear synergy: combinations of dimples with pin-fins, ribs, or jets can achieve higher augmentation than dimples alone. However, these benefits are usually accompanied by higher friction factors and pressure losses. Thus, hybrid approaches require careful optimization of geometry (δ/D, pitch, density) and operating conditions (Reynolds number, turbulence intensity) to maximize performance evaluation criteria (PEC).

2.9 Applications Across Industries

The unique ability of dimpled surfaces to provide significant heat transfer augmentation with relatively modest hydraulic penalties has facilitated their adoption in multiple industrial sectors. Their versatility extends from large-scale energy systems to microscale cooling devices,

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making them a critical passive enhancement strategy across diverse applications.

2.9.1 Gas Turbines and Aerospace Cooling

Gas turbine blades and combustor liners operate under extreme thermal loads that require efficient cooling strategies. Chyu et al. [3] and Mahmood et al. [4] demonstrated that concavity-based and dimpled passages provide up to 2.5 times augmentation over smooth surfaces, ensuring reliable blade cooling. Moon et al. [31] confirmed that dimpled cooling passages in turbine blades deliver improved wall temperature uniformity compared to ribbed surfaces, reducing hotspots and extending component life. Ligrani et al. [6] further validated that staggered dimple arrays balance heat transfer with acceptable frictional penalties, making them well-suited for aerospace applications.

2.9.2 Automotive and Compact Heat Exchangers

In automotive systems, compactness and efficiency are vital. NatVorayos et al. [18] experimentally verified that staggered dimple arrays in compact plate-fin exchangers improved thermal–hydraulic performance compared to smooth channels, supporting lightweight and energy-efficient automotive radiators. Leontiev et al. [19] also reported that incorporating dense dimple arrays reduced the size of compact heat exchangers while maintaining efficiency. These results emphasize dimples as an effective enhancement technique for the automotive sector, where both thermal performance and reduced pumping power are critical.

2.9.3 Electronics Cooling and Micro-Scale Applications

Electronics cooling requires high heat flux dissipation in confined spaces. Vorayos et al. [7] investigated staggered dimple arrangements in microchannel systems, showing enhanced heat transfer while avoiding the excessive pressure penalties associated with traditional roughness elements. Burgess and Ligrani [8] extended this to dense electronic cooling passages, where optimized δ/D ratios ensured thermal enhancement with manageable drag. Such findings underline the relevance of dimple-based strategies in addressing the challenges of next-generation compact and high-power electronic devices.

2.9.4 Chemical and Process Industries

The chemical and petrochemical sectors rely heavily on process heaters and recuperators, where efficient heat transfer with minimal maintenance is essential. Chudnovsky and Kozlov [1] reported successful field trials of dimpled-tube technology in chemical industry process heaters, showing both improved thermal performance and robust durability under field conditions. These trials demonstrated the industrial readiness of dimple-based solutions beyond laboratory-scale studies.

2.9.5 Biomedical and Emerging Applications

Although less common, dimpled surfaces have also been considered in biomedical and cryogenic systems. For example, Afanasyev et al. [2] highlighted the potential of dimples in laminar and transitional regimes relevant to cryogenic cooling. Recent cold-surface studies [30] indicate their suitability for precoolers and medical cooling devices, where laminar operation dominates. The ability to deliver heat transfer augmentation under laminar conditions widens the scope of dimples into emerging biomedical applications, where compactness and reliability are critical.

2.9.6 Summary of Industrial Relevance

Across industries, the adoption of dimpled surfaces has been driven by their ability to:

Improve heat transfer while minimizing hydraulic losses.

Provide flexibility across scales—from gas turbines to microelectronics.

Adapt to hybrid configurations with ribs, fins, or jets for maximum augmentation.

These diverse applications confirm the practical value of dimples and highlight why continued experimental and computational research remains vital, particularly in underexplored areas such as cold surfaces and laminar flows.

2.10 Summary of Literature and Identified Gaps

The review of literature on convective heat transfer enhancement techniques demonstrates significant progress in

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both experimental and computational investigations. Conventional methods such as ribs, fins, corrugated surfaces, and twisted tapes have been widely studied [9], but these approaches generally incur high pressure drops, which limit their thermal–hydraulic efficiency. The introduction of dimpled surfaces provided a breakthrough, offering a balance between enhanced heat transfer and moderate friction penalties. Early studies confirmed that dimples generate counter-rotating vortex pairs that periodically shed downstream, disrupting the boundary layer and producing locally high Nusselt numbers [2], [3], [4], [5].

A considerable body of work has focused on geometric parameters, including depth-to-diameter ratio (δ/D), pitch, array density, and arrangement (inline versus staggered). Findings consistently show that:

Increasing δ/D intensifies vortex strength and heat transfer but raises friction factors [8], [32].

Staggered arrays outperform inline configurations due to stronger vortex interactions [7], [18], [19].

Optimal pitch and density exist, beyond which frictional penalties outweigh thermal benefits [19].

Shape variations, such as ellipsoidal and oriented dimples, can enhance laminar flow performance [28], [29].

Flow regime dependence has also been extensively explored. In turbulent conditions, dimples are highly effective, with augmentation up to 2.5 times greater than smooth surfaces [3], [4], [6], [31]. In transitional regimes, dimples accelerate turbulence onset,

thereby improving efficiency at lower Reynolds numbers [18], [19]. However, in laminar flows, augmentation levels remain modest, with limited systematic data available [2], [28], [29].

Computational fluid dynamics (CFD) studies have complemented experiments, validating vortex dynamics, local Nusselt distributions, and sensitivity to geometry using RANS, LES, and hybrid turbulence models [6], [8], [18], [19]. These studies provide deeper insight into the mechanisms of augmentation, though validation against experiments remains critical.

Hybrid approaches—such as combining dimples with ribs, pin-fins, or impinging jets—have shown synergistic effects, yielding higher augmentation but often at the cost of increased pressure losses [3], [4], [6], [18], [31]. Industrial applications across gas turbines, automotive heat exchangers, electronics cooling, and process heaters confirm the practical relevance of dimples [1], [7], [18], [19], [31].

Despite this progress, several critical research gaps remain:

1. **Limited cold-surface studies** – Most experimental investigations focus on heated surfaces, while cold walls, relevant to cryogenic precoolers and chilled-water systems, are underexplored [30].

2. **Sparse laminar flow data** – Dimple effects under laminar regimes remain poorly understood compared to turbulent flows, especially for cold-wall conditions [2], [28], [29].

3. **Systematic hot–cold comparisons** – Few studies directly compare heated and cooled surfaces with identical geometries and Reynolds numbers, limiting generalized design correlations [18], [19].

4. **Thermal–hydraulic optimization** – Existing correlations emphasize augmentation but often overlook performance evaluation criteria (PEC), where balancing heat transfer against pressure losses is critical for practical adoption [8], [19], [32].

I. Link to Present Research

The identified gaps highlight the need for controlled experimental studies comparing heated and cold dimpled surfaces under laminar flow conditions. This thesis directly addresses this gap by:

- Investigating the effect of pitch and density variations on convective heat transfer.
- Conducting systematic trials under both hot and cold wall conditions.
- Evaluating Nusselt number trends and PEC values across laminar Reynolds numbers.
- Providing experimental data to support improved design guidelines for compact heat exchangers and laminar-flow thermal systems.

Thus, this work contributes to bridging the literature gap by offering a comprehensive experimental database and

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comparative analysis for heated versus cold dimpled surfaces in laminar flow, thereby extending the applicability of dimples into underexplored operational domains.

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