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Advances in Oscillating Fin Technologies for Heat Transfer Enhancement: A Review of Numerical and Experimental Approaches

Dheya Ghanim Mutasher*

Mechanical Engineering Department, University of Technology-Iraq, 10066 Baghdad, Iraq

* Correspondence: Dheya Ghanim Mutasher (20075@uotechnology.edu.iq)

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Abstract: The enhancement of heat transfer continues to be a critical objective across various high-performance applications, including electronics cooling, automotive thermal systems, and renewable energy systems. Among emerging passive and active strategies, oscillating fin technology has attracted growing interest due to its potential to disrupt thermal boundary layers and augment convective heat transfer. In this review, a systematic analysis of 120 peer-reviewed studies indexed in Scopus, Web of Science, and Google Scholar was conducted, employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to ensure transparency and reproducibility. Search terms such as "oscillating fins," "heat transfer enhancement," "numerical simulations," and "experimental techniques" were used to capture the breadth of relevant literature. Emphasis was placed on the interplay between oscillation parameters—namely frequency, amplitude, and mode of oscillation—and fin geometry, with particular focus on their influence on local and average heat transfer coefficients. Numerical methodologies, including Computational Fluid Dynamics (CFD) and Finite Element Thermal Analysis (FETA), were utilized extensively to characterize fluid motion and thermal gradients around oscillating structures. The reliability of these simulations was critically assessed in light of experimental validations, with instrumentation precision and laboratory conditions considered as key metrics of model fidelity. Challenges related to continuous fin movement, mechanical fatigue, and manufacturing constraints were also identified. To address these issues, recent developments in fatigue-resistant composite materials and advanced fabrication techniques—such as additive manufacturing—were reviewed. Furthermore, the incorporation of novel materials, including porous metals, nanofluids, and piezoelectric components, was explored for their synergistic effects on thermal performance and system durability. This review not only consolidates the current understanding of oscillating fin mechanisms but also highlights gaps in knowledge and opportunities for future research in the development of high-efficiency thermal management systems.

Keywords: Oscillating fins; Heat transfer enhancement; Numerical simulations; Finite thermal management; Experimental techniques; Advanced materials; Nanofluids; Piezoelectric systems; Fin design innovations

1 Introduction

Effective thermal management is usually required in many engineering applications; hence, heat transfer is important. During the past decades, there has been a huge research effort to improve heat transfer techniques in addressing constraints on cooling electronic components and in industrial heat exchangers. Since the demand for advanced thermal solutions increases, it is necessary to understand the oscillating fin heat transfer.

Every engineering application, especially with today's advanced devices, needs effective thermal management since heat is increasing. Heat exchangers without movement used to be the main technology applied to boost convective heat transfer. Yet, these fins cannot easily avoid the accumulation of heat-blocking layers near the body and often lack the ability to be made small yet operate efficiently. To deal with these issues, people have started seeking new solutions for static fins.

Such technology is considered a good option since it creates rapid movements that eliminate stuck surfaces and encourage better mixing of the fluid involved. Oscillating fins cause a strong increase in turbulence, which results in increased heat transfer compared to still fins. The approach is beneficial for confined spaces since it provides better heat management, lower thermal resistance, and may save energy. Therefore, it is well-suited for cooling electronics as well as systems powered by renewable energy.

Oscillating fin systems are much easier to manage and study using numerical modeling. Since they accurately model complex situations in fluids and structures, CFD and Finite Element Analysis (FEA) are largely used by engineers in this area. Even though other approaches are available, CFD and FEA are highly developed, provide effective tools, and can model the important transient and combined issues in these types of systems. By using both, it is possible to investigate the expected thermal and mechanical behavior of fins under realistic working situations.

This study explains the background for using oscillating fins and describes the reasons for using numerical methods to further investigate and apply this technology for better thermal management.

The addition of such fins is good for heat transfer since it allows mechanical oscillations to disrupt boundary layers and facilitates fluid dynamics around the fins. It is a method that can provide significant improvement of thermal performance, in particular in compact systems where there is a lack of space. But with electronic devices compacting while getting more powerful, the problem of heat generation becomes even more significant. Efficient cooling without growing system size and weight might be achieved using oscillating fin technology.

Conduction, convection, radiation, and other heat transfer principles are all relevant but this discussion addresses the convective mechanisms by means of oscillatory motion. Fins vibrate to induce turbulence that helps mix boundary layer fluid near the fin surfaces and increases the local heat transfer coefficient and decreases thermal energy bias to heat sinks or exchangers. By adding such active strategies as oscillation, the external energy to the system is very active, with a huge increase in thermal performance and an enormous reduction in energy demand as opposed to traditional methods. More and more research is looking into the integration of active and passive processes in order to achieve the best results.

Many research studies have been conducted examining the effect of various parameters, like oscillation frequency and amplitude, on heat transfer rates in many instances requiring the use of high-order modeling tools like CFD or FEA to predict the system behavior at different operating conditions.

Changes in industry trends of efficiency and decreased environmental impact represent innovations in fin design. New materials, coatings, and configurations are being examined by researchers to optimize performance. Oscillating fin technology promises, but durability is an issue during continuous operation, and manufacturing is complex. In general, oscillating fin heat transfer is an innovative solution to globally ubiquitous thermal management issues involved in a wide range of applications [1–7].

2 Fundamentals of Oscillating Fin Heat Transfer

2.1 Principles of Heat Transfer

Due to the importance of heat transfer in engineering, thermal management systems encompass an array of heat transfer processes. The heat transfer coefficient of a system is governed by three primary mechanisms of conduction, convection, and radiation, which each affect the heat transfer coefficient. Heat transfer by conduction is similar to that occurring at the microscopic level, as particles collide and transfer heat energy. Fourier's law, which asserts that heat flux is proportional to the negative sign of the temperature gradient, describes this; the role stress plays is also acknowledged, which places a strong emphasis on the thermal properties of the material.

Convection can be divided into two types: natural and forced. Natural convection is heat exchange with a moving fluid with a solid surface; in that case, the fluid flow happens due to the existence of feedback between the temperature and fluid properties, like viscosity and thermal diffusivity, which may depend on the temperature of the fluid. Buoyancy effects resulting naturally from temperature differences between the fluid result in natural convection and flow patterns depending on density variations within the fluid. However, forced convection is with the use of external forces—fans or pumps—which move the fluid. With higher velocities, convective heat transfer is improved, subject to effects such as viscosity and surface area. When compared to conduction and convection, radiation does not use a medium for the transfer of energy and is done by electromagnetic waves emitted from heated surfaces. All bodies, as per the Stefan-Boltzmann law, radiate thermal energy based on their temperature, and this can significantly impact the shape of heat exchange efficiency in heat exchangers.

The principles are enhanced by incorporating mechanical vibration in heat exchangers through the use of oscillating fins to disrupt boundary layers on fin surfaces. Turbulence is increased and thermal resistance is reduced over static configurations. Such a phenomenon as "lock on" occurs when the oscillation frequency is matched with a natural shedding frequency of vortices, which further enhances turbulence and fluid mixing. In addition, the structural integrity and efficiency of slotted fins and advanced materials are enhanced without placing additional energy input. These are the principles that will allow us to create innovative systems to address modern challenges in energy consumption and sustainability [2, 6, 8–10].

2.2 Mechanisms of Oscillation

Fundamentally, the interaction of oscillation in fin heat transfer systems is caused by the dynamic interaction of the various fluid movements and the vibrating surfaces of the fins. Such interactions can greatly improve the thermal efficiency through changes in flow dynamics and effective mixing of the fluid for better heat transfer rates. Secondary flows induced by oscillating fins disrupt the thermal boundary layer, which is essential for increasing the convective heat transfer. Particular relevance is given to this phenomenon when natural or forced convection has a significant role to play with cooling processes.

Frequency and amplitude of oscillation play a critical role in oscillation. Studies have proved that these variables can result in very changeable thermal performance. For example, increasing oscillation generally increases the heat transfer rate by inducing greater fluid movement, which raises shear stress at the fin surface and improves convection. On the other hand, it is important to have the optimal frequencies to prevent the undesired effects, such as over-vibrations leading to structural fatigue or the lack of effective mixing.

Equally important in converting oscillations into heat transfer improvement is the fin design. By including flexible materials in configurations, further improvements in thermal efficiency can be achieved depending on variations in flow conditions. For instance, the fins can perform harmonic oscillations that are synchronized with fluid vortices, resulting in an enhanced convective current at these fins. It creates the lock-on effect, leading to continuous renewal of boundary layers and, at the same time, increasing the effective heat exchange area. Furthermore, it was found that the interaction between oscillating fins and various types of fluids, including special types of fluids such as nanofluids, is different. The synergy increases the benefits of fin oscillations thanks to a thermal conductivity and viscosity boost due to the introduction of the nanoparticles. On the one hand, research conducted in controlled cavity setups has indicated that both frequency and amplitude of the structures can significantly affect heat transfer rates when nanofluids are deployed to harness oscillating structures.

Several numerical methods have been used to properly model these complex interactions. Such advanced thermofluid analysis techniques as CFD may be employed to perform fluid structure interaction (FSI) simulations in which the factors relevant to the design of fins, including the behavior of fluid on the fin, are accounted for, and external influences, including temperature gradients, are taken into consideration. Particularly useful in addressing the obstacles encountered when dealing with fin vibrations involved in moving boundaries has been the Arbitrary Lagrangian-Eulerian (ALE) method. By adopting these mechanisms, the engineers can optimize fin designs according to the applications, such as electronic cooling systems or industrial heat exchangers, and develop solutions fit for the target ranges of the performance metrics [1, 2, 4, 11–15].

2.3 Effects on Thermal Performance

The mechanisms that enhance thermal behavior play a role in determining the performance of oscillating fin heat transfer systems. Oscillation provides an interaction between fins and fluid flow, minimizing thermal boundary layers and enhancing the heat transfer rates, improving the efficiency of stationary systems. This movement produces the vortices that, in turn, increase the amount of mixing in the fluid, and thus the heat transfer coefficient is higher than in non-oscillating systems.

Experimental research suggests that fins oscillate by a factor of ten or more and which can significantly improve thermal management, where other designs cannot. Using studies of three-dimensional printed aluminum finned radiators, thermal resistance decreases from 0.32 C/W to 0.11 C/W in solid constructions, and decrease in steady-state heat dissipation. For thermal efficiency, these critical parameters have to include frequency and amplitude of oscillation. Under forced convection, convective heat transfer is increased by the increase of turbulence as it moves closer to the fin surface. Increasing vibration amplitude will increase performance, up to some point; past that, there may be diminished returns or mechanical issues.

Moreover, the thermal performance of fins is affected by their structural arrangement. Geometric optimization plus oscillations at lower flow rates can dramatically improve effectiveness in research on micro-pin fin designs. The improved vortex dynamics lead to these adjustments, which increase surface area for heat exchange, as well as maintain higher local velocities.

In addition, nanofluids have been investigated for use in oscillating systems to increase their thermal efficiency insofar as nanofluids can provide better convective properties and wettability in dynamic operation. Currently developing innovations, such as elastic vibrating surfaces, are used to completely rethink efficiencies in engineering disciplines and include electronics cooling and energy conversion. Finally, although the mechanisms of oscillating fin heat transfer have been understood and optimized to some extent, there are still challenges to be addressed and new materials or configurations to explore for better thermal management in a variety of industries [1, 3, 8–10].

3 Fundamentals of Oscillating Fin Heat Transfer

Understanding how the various parts of an oscillating fin heat transfer system function requires the use of numerical methods. To use these methods, the primary goal is to address the linked equations that describe fluids and heat by using CFD and FEA.

These models use a calculation primarily for convection and conduction, but often the term for radiation is not added. Even though radiation plays an important role in some high-temperature processes, most studies for oscillating fins focus on convection due to its simplicity. In the future, it would be useful to make radiative heat transfer part of the model where radiation is significant in the scenario.

Important factors such as the frequency, amplitude, and ways to measure temperature are key to confirming numerical models, though their descriptions are rarely detailed. In most cases, the selected frequency ranges cover what is needed for the machine to run smoothly, from a handful of full Hz to a few hundred Hz. The temperature inside the fins and throughout the heat exchanger is routinely measured with thermocouples or by looking at the surface temperature with an infrared (IR) device. To achieve accurate results for model validation, it is important to ensure the instruments used are properly set up and calibrated.

3.1 CFD Models

3.1.1 Governing equations

To understand the dynamics of thermal enhancement by oscillations, one needs to solve the equations governing heat transfer in oscillating fin systems. The Navier-Stokes equations and thermal energy equation are the former of these and describe fluid behavior and transport phenomena around oscillating fins.

Key equations include the following:

a) The continuity equation for incompressible flow

$$\nabla \cdot \mathrm{u} = 0$$

where, u is the velocity vector.

b) The momentum equation

$$\rho(\partial u/\partial t + u \cdot \nabla u) = -\nabla p + \mu \nabla^2 u + f$$

where, ρ is the fluid density, p is the pressure, μ is the dynamic viscosity, and f is the body forces.

c) The energy equation

$$\rho C_p(\partial T/\partial t + u \cdot \nabla T) = k\nabla^2 T + Q$$

where, C_p is the specific heat capacity, T is the temperature, k is the thermal conductivity, and Q is the internal heat generation.

In addition, these equations must now be time-dependent due to the fact that oscillating fins have periodic oscillations in base temperature or fin geometry. For instance, it is possible to model sinusoidal variations in base temperature: $T_{b(t)} = T_m + A\sin(\omega t)$, where T_m is the mean temperature, A is the amplitude, and ω is the angular frequency.

A lot of coupled Partial Differential Equations (PDEs) need to be solved using numerical techniques, as limited by finite volume or finite element. These calculations are enabled by such software as OpenFOAM or COMSOL Multiphysics, which adopts nonlinear dynamic mesh methods to recap the geometric change while oscillating at various flow states. In cases involving natural convection affected by toggling fins, material properties and geometrical dimensions need to be accounted for to comprehend patterns and thermal dynamics of flow. Additional complexities from research on flexible fins or hybrid control strategies include modifications in Nusselt numbers that increase the convective heat transfer rates.

The ability to understand how oscillatory actions produce their effect upon thermal performance is essential to the development of the ongoing trend to reduce operational efficiencies in applications such as industrial cooling systems [2, 15–18]. Figure 1 shows the diagrams depicting the topic under study.

3.1.2 Boundary conditions and assumptions

An exploration of the numerical analysis of heat transfer in oscillating fin systems relates to the boundary conditions and the underlying assumptions involved. An accurate flow characteristic definition is necessary to provide for effective modeling. In general, it is considered to have incompressible and laminar flow or turbulent flow with respect to Reynolds numbers pertinent to the specific problem being investigated. A long literature suggests that the incompressibility assumption in oscillating systems simplifies the governing equations without degrading the accuracy of the results.

A one-dimensional heat transfer framework, which facilitates mathematical description, is used by most of the studies. It makes this specific assumption that temperature gradients along the length of the fin are much larger than across its width. Fourier's law for conduction and Newton's law of cooling for convection are usually used to describe heat transfer rates. This material will expand on these principles to give a solid foundation on how thermal energy moves through the fins as well as the surrounding fluid medium. The usual case of boundary conditions is fixed temperatures or convective heat exchanges at the base of the fin, which may change along its length. In cases of mechanical oscillation, one should know the influence of these oscillations on thermal efficiency. One such example is the case where vortex shedding happens quite close to that of a flexible fin's natural frequency, at which time the turbulence and mixing in the boundary layer can be enhanced by the increased turbulence and mixing to yield substantial gains in heat transfer.

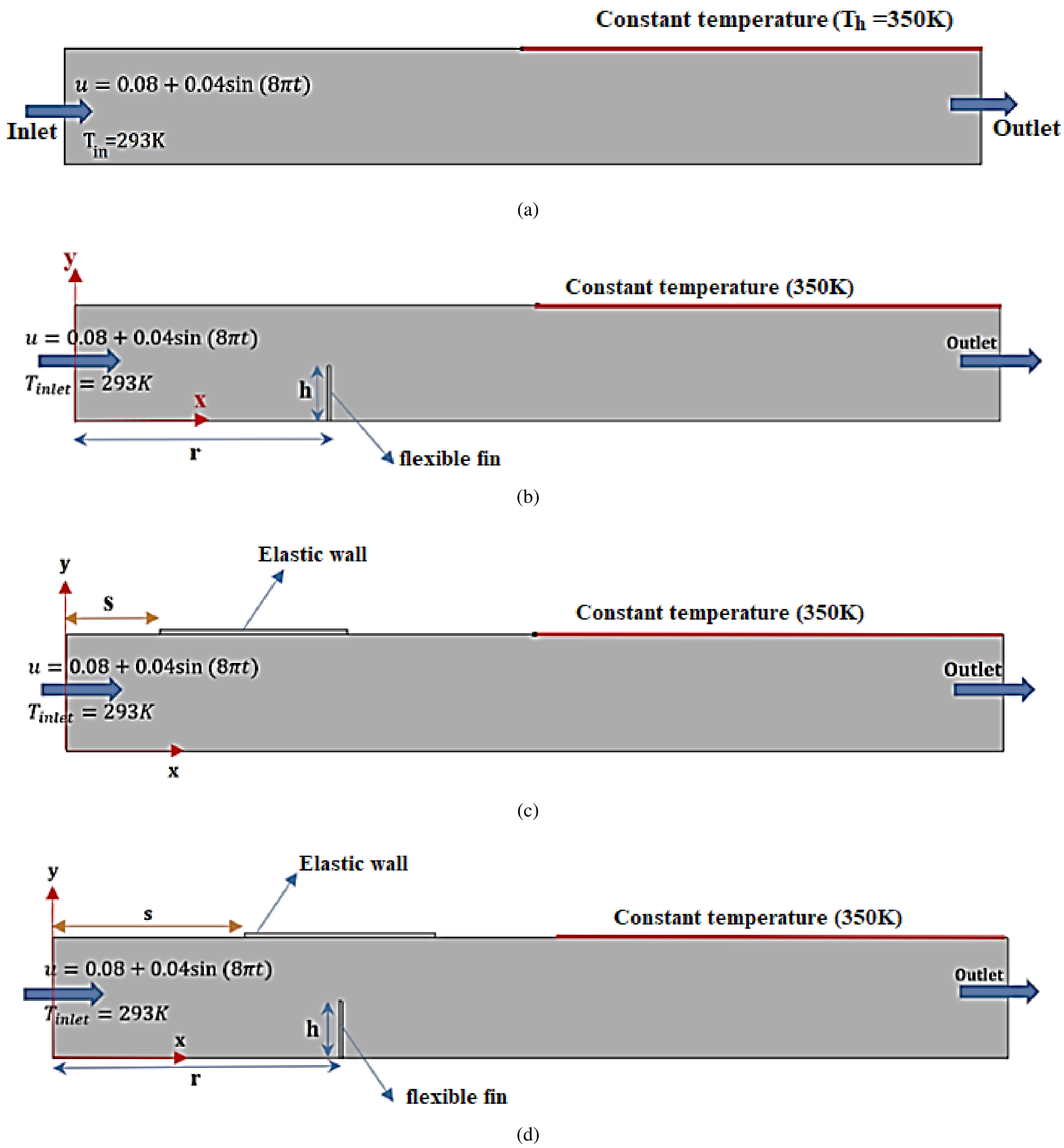


Figure 1. Diagrams depicting the topic under study: (a) having no flexible fin and no elastic wall, (b) having a flexible fin and no elastic wall, (c) having an elastic wall and no flexible fin, and (d) having both [16]

Many models also assume that the thermal properties remain uniform during an analysis period. However, the operation of some advanced frameworks may include temperature-dependent properties when there are large temperature variations between these operational ranges. Therefore, it can have a more nuanced understanding of the way heat conduction occurs in various conductive materials that are subject to changing temperatures.

Furthermore, parameters such as heat transfer coefficients may also be treated as variables over the lengths of fins due to the use of empirical correlations based on available experimental data or in the literature. By including these dynamic elements, simulations are produced that are more realistic of real-world operating conditions. In addition, and traditionally, such analyses of flexible fins under oscillatory actions also include elastic properties, which are often simplified by assuming the same elastic properties throughout the length of the fins unless data or advanced material considerations otherwise dictate.

The final outcome is that using these assumptions allows researchers to develop computational models that agree with practical applications that are also manageable in complexity and time computational demands. These models should always be validated against experimental data in order for their predictive capabilities to as closely approximate observed phenomena as possible. The need to balance assumptions with practical realities is still an important aspect of the optimization of our knowledge of oscillating fin heat transfer systems [17, 19–21].

Typically, CFD and FEA simulations are based on the idea that fluids do not compress, the flow state depends on the Reynolds number and this is done at a constant temperature value over the chosen range. Typically, the heat flux and velocity stay constant at the base of the fin, the walls of the fin do not rotate with the fluid, and the movement and frequency at the fin boundaries are determined. Temperature change for variables like elastic moduli and thermal conductivity is usually ignored unless modeled in the calculations. By using these simplifications, the problem can be easily solved, and it is necessary to make sure they are clearly explained in the model.

3.2 FEA Approaches

FEA is critical to the study of oscillating fin systems, where it can be used to make detailed investigations of the many processes involved in oscillating fin system heat and fluid transfer systems. The governing equations of the fluid flow, the heat transfer, and the structural interaction are decomposed under this method to shed some light on the intricate behaviors of oscillating fins under different operational conditions. This section investigates the application of FEA to model oscillating fin designs and identifies the critical parameters affecting these designs' performance. The ALE approach is usually used in the FEA study of oscillating fins in order to accurately depict both fluid and structural parts. Using this approach, the feasibility of simulating the fins' moving boundary, resulting from their oscillatory motion, is introduced, and FSI is integrated. Several studies have been performed to show that oscillation frequency, amplitude, and the thermal conductivity ratios between the fins and surrounding fluids are major factors determining the heat transfer rate.

Recent innovation has shown that resonant fin oscillations with the amplitude and frequency simultaneously enhanced can result in a significant enhancement of heat transfer efficiency. For example, higher frequencies will allow more uniform velocity distribution over the fins, resulting in a rejuvenated thermal boundary layer, causing more frequent convective heat transfer. Thus, the Nusselt numbers benefit from these dynamics in cavity systems with either flexible or rigid fins.

FEA also provides a means to explore every parameter relating to the design modifications that improve performance. Fin length and fin material composition changes are also shown to directly reduce thermal conductivity and overall efficiency. Importantly, the elastic properties or material selection under which elastic flexural capabilities can be improved without impacting the convective currents in the adjacent fluids illustrate a beneficial relationship between the mechanical flexural ability and heat transfer. It also considers a study of boundary conditions, which are essential for achieving accurate simulation. The sensitivity to aspects such as the initial temperature distribution, wall conditions (adiabatic or isothermal), and external flow characteristics is routinely carried out as part of the sensitivity analyses pertaining to system behavior under realistic operating conditions.

The reputation of results obtained from FEA is usually validated by using experimental data. However, the emphasis placed on the validation phase allows numerical results to be aligned with physical observations; any discrepancy serves as a valuable piece of information about where the models used might need to be improved and possibly changed. Overall, finite element techniques offer great ideas about how oscillatory motions affect thermal efficiency via advances in integrating mechanics with fluid dynamics. The advances in this field continue through the application of the powerful capabilities of FEA to further optimize the oscillating fin technology and to address the complexities of the interactions in these systems [1, 11, 15, 22].

4 Experimental Techniques for Heat Transfer Augmentation

Numerical models must be verified, and the performance of oscillating fin heat transfer systems can be explored using experiments. Even so, fin material information, including Young's modulus, fatigue limit, and damping, is not always given in detail. This has a direct role in deciding whether fins will remain strong and rhythmical when stressed and exposed to temperature changes. To ensure that a device stays reliable during constant oscillation, its mechanical properties must be well understood and characterized.

Frequency, amplitude and shape of the vibratory waveform should be studied more closely to know their effect on heat transfer. Experiments have proved that increasing vibration frequency tends to improve convective heat transfer as it mixes the fluid better and disturbs boundary layers formed on a surface. However, too high a frequency might strain and weaken the materials, which can result in a drop in the system's efficiency. Vibration amplitude also influences the intensity of moving fluid and ought to be controlled to ensure the structure is not damaged. It is necessary to analyze the vibration data through parameters that relate to thermal measurements, such as the Nusselt number and the heat transfer coefficient.

What researchers select as materials and how they set the temperature and environmental settings can have a big impact on the results achieved. As an example, certain materials become better at dissipating heat, but they cannot handle as many stresses and strains as others. The environmental factors of air temperature, barometric pressure, and humidity must be checked and noted precisely, as these environments affect both the heat transfer occurring in a material and its behavior. As a result, it is often necessary to describe individual factors because the relationship between material and oscillation parameters tends to make the overall work more complicated. Simply put, adequate analysis and evaluation of mechanics, vibratory behavior and material-environment relationships are necessary for improving studies and practical use of oscillating fin heat transfer systems.

4.1 Laboratory Setup and Methodology

A carefully designed laboratory setup is needed in order to conduct experimental investigations of heat transfer in oscillating fin systems. More often than not, it is a setup with a controlled environment, enabling one to make precise changes on variables such as temperature, pressure, and oscillation frequency. For example, an experimental apparatus is often an insulated chamber that insulates the experimental system against external thermal disturbance and mounts a number of heat exchangers with oscillating fins.

Thermal sensors, such as thermocouples, are placed at critical locations—specifically at the base, the evaporation zone, and the condensation region of the heat exchanger—as these are important parts of this setup. During the operation, temperature variations are measured over different parts using multiple thermocouples. In particular, in the case of experiments in which flat plate oscillating heat pipes are used, thermocouples are geometrically arranged tangentially to the fins to monitor the temperature gradient and assess the heat dissipation efficiency. Methodology is presented in terms of adjusting heating power to see how it affects performance metrics. Reaching robust data on operational characteristics is done by gradually increasing the input power (usually by increments, e.g., 20 W to 140 W), letting each condition stabilize for a predetermined amount of time (usually around ten minutes), and then checking it. And these well-established protocols do exactly these two things to increase consistency with experiments and to improve accuracy with data.

Transporting liquids or gases within the system has to be done with some form of flow restriction, or the transport of fluid would not take place at all. Through the use of pressure gauges that accurately measure pressure on the flow path of the heat exchanger design, researchers can determine how oscillation affects fluid or thermal dynamics in the heat exchanger.

As important is the thorough documentation of all the experimental parameters in each trial. It includes the recording of other factors, such as fluid properties (viscosity and density), that can make a big difference in heat transfer behavior under oscillating conditions. The automation of this process by data logging systems has been commonly used to minimize human error. Additionally, the experimentation itself may involve modifications to test samples between trials in fin geometries and materials. For instance, it may entail switching between various cross-sectional designs or utilizing some new advanced materials that are good in terms of thermal conductivity or thermal resistance. This modification of the design helps us to understand the effect of structural changes on the overall efficiency under convective flow by oscillation.

The experimental approach is also another essential part, where a number of repeats are also conducted under similar conditions to obtain the reproducibility of results. Confidence in the observed heat transfer rate improvements due to the oscillation mechanisms is increased through consistent outcomes. However, via this entire comprehensive experimental framework of setup design and data collection methods, researchers can obtain meaningful conclusions about the effectiveness and applicability of different oscillating fin designs for heat transfer performance improvement across different applications [3, 9, 23–26]. Figure 2 shows the distribution of thermocouples.

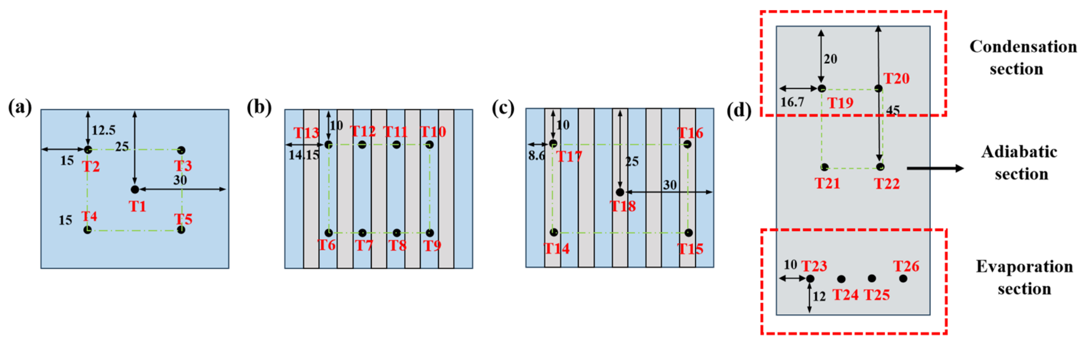


Figure 2. Distribution of thermocouples at the (a) bottom, (b) evaporation end, (c) condensation end, and (d) fins of the FOHPFR [9]

4.2 Measurement Techniques and Instrumentation

Measurement techniques and instrumentation are necessary for determining heat transfer efficiency in the oscillating fin system. These measurements are very dependent on the quality. Therefore, the reliability of the experimental data is very much dependent on the quality of these measurements.

The commonly used instruments are thermocouples, pressure sensors, and flow meters. For tracking temperature changes for different sections of the oscillating fins, thermocouples are needed. Multiple thermocouples are placed at the critical points of the heat pipe, i.e., at evaporation and condensation zones, in the studies performed on oscillating heat pipes for the detailed thermal profiling. For instance, straight fins can be arranged vertically so that eight thermocouples mounted there can be used to capture the oscillation effects adequately.

The ability to measure pressure sensors is important for fluid dynamics in oscillating systems. The results they provide are data on pressure drops due to different fin configurations in order to evaluate convection performance and overall efficiency metrics in terms of the resistance of the heat exchanger. Air mass flow rates through fin channels have to be measured for determining convective heat transfer coefficients (h) that show the way air interacts with the heated surfaces. The air-side thermal absorption and the water-side dissipation metrics are accounted for in the calculation of these coefficients. Experimental insights into oscillatory behaviors are also advanced by advanced imaging techniques. Researchers are able to view fluid motion and dynamics in fluids noninvasively, and through high-speed imaging, relate oscillation amplitudes to thermal performance indicators, such as contributions of latent vs. sensible heat.

Another novel method for measuring the heat flux distribution is IR imaging of interfaces where fluid meets solid surfaces. The combination of IR imagery with high-speed visualizations enables researchers to separate contributions from the two heat types to better understand their role in improving predictive models for efficiency under different conditions.

In addition, pulsating heat pipe (PHP) instrumentation advancements require rigorous testing, as PHPs operate in a unique fashion. To obtain reliable thermal performance results for a specific system design, operational parameters (s) need precise calibration to emulate realistic working conditions. When it comes to applying traditional sensors in conjunction with modern imaging methods, the understanding of systems that contribute to better thermal performance in active cooling is improved [3, 9, 23, 27, 28]. Figure 3 illustrates a single enlarged fin and the corresponding control volume used in the heat balance analysis. The region highlighted in dark in subgraph (a) of Figure 3 is magnified in subgraph (b) of Figure 3 to provide a clearer view of the computational domain. Several key calculations necessary for determining heat transfer characteristics in heat exchangers are addressed in the subsequent discussion. Of particular importance is the determination of the optimal length (l_c) of the heat exchanger. This length is derived based on the peak-to-peak displacement of the working gas. To maximize thermal performance, the value of l_c should correspond closely to the full extent of the oscillatory motion exhibited by the working gas [27]. Figure 4 shows the heat transfer versus drive ratio at different mean pressures [28].

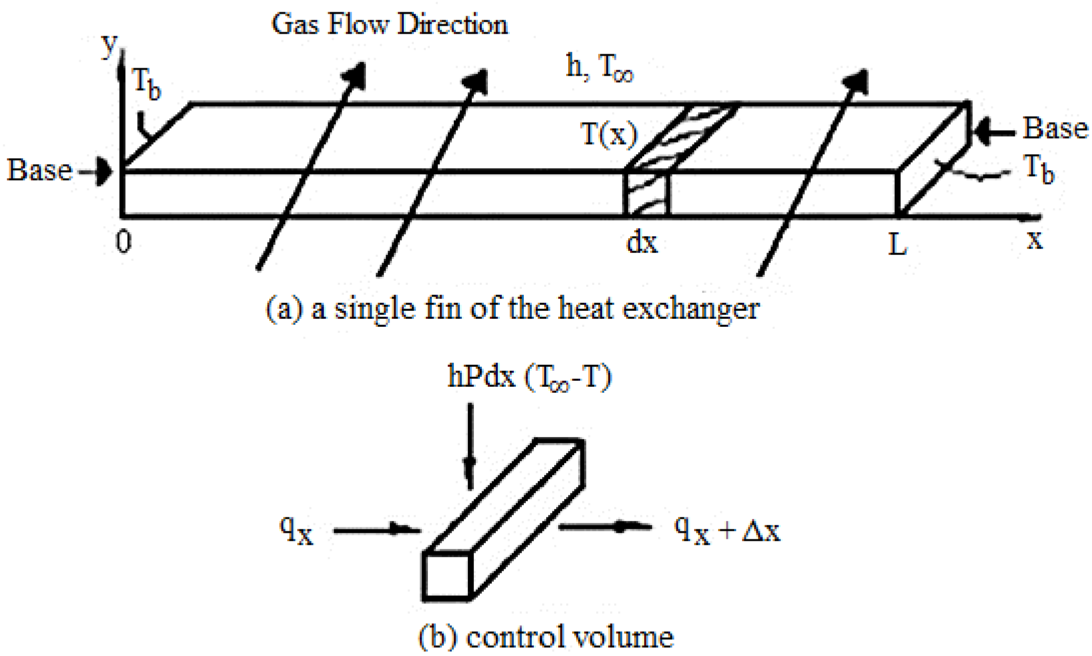


Figure 3. Enlarged fin geometry and control volume for heat transfer analysis [27]

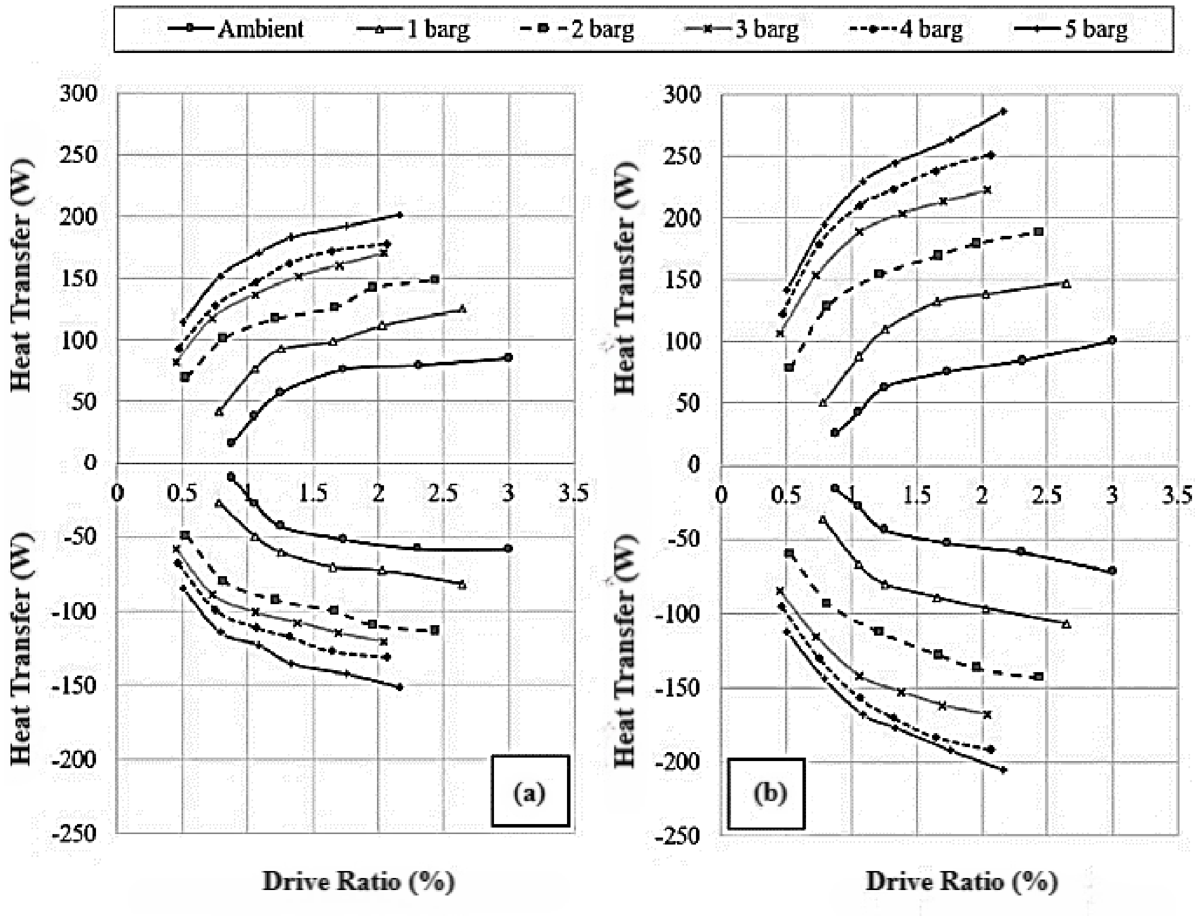


Figure 4. Heat transfer versus drive ratio at different mean pressures: (a) steel heat exchangers and (b) aluminum heat exchangers [28]

5 Innovations in Oscillating Fin Designs

Better materials, manufacturing techniques, and design changes are major reasons behind recent innovations in oscillating fins in the energy industry. As a result, additive manufacturing, particularly 3D printing, has made it easier to shape fins with user-defined porosity and detailed structures inside them that are rarely produced using regular techniques. Researchers have discovered that 3D-printed porous fins can feature porosity levels up to 70%, raising their surface area and (as a result) combating heat loss by increasing turbulence. Additionally, having less porous materials means the parts are lighter and may be cheaper, but there is a loss in some strength. Usually, visualizing the trade-offs between innovative designs in terms of thermal conductivity, pressure drop, manufacturability, durability, and cost can be done by using radar charts. By comparing fins, one can find their pros and cons and see which ones need improvement in the future.

It further introduces the idea of using Phase Change Materials (PCMs) to help regulate thermal energy using oscillating fins. Nevertheless, one should remember that waxes belong to organic PCMs because they hold a high level of latent heat but do not conduct heat efficiently, while metal-based PCMs provide good heat conductivity but can cost more and be tricky to implement. Because of this, the method by which heat is handled determines which materials are chosen.

Moreover, using piezoelectric materials in active oscillating fin systems helps generate needed vibrations and jets of water. Before choosing a material, you must compare the highest performance of PZT with the flexibility and affordability of Polyvinylidene Fluoride (PVDF). For piezoelectric-enhanced thermal systems to grow, their costs, the way they function, and their impact on the environment must be considered.

5.1 Advanced Materials and Coatings

Oscillating fin heat exchangers are dependent on innovations in materials and coatings to increase the effectiveness of heating. The development of revolutionary materials has included elastic, thermal conductivity, and structural integrity for additively manufactured parts. However, as an example, metal foams have high porosity and elaborate skeletal structure, leading to a much higher heat transfer area while reducing the weight of the system. Foams that disrupt the thermal boundary layer are used effectively to enhance turbulence and improve heat transfer performance. They can be used in cooling electronics as well as a number of industrial processes. One further advance in the technology of heat transfer is the use of porous fins. Secondly, these fins provide an otherwise unavailable expanded surface area for heat exchange plus fluid flow through design, greatly improving thermal performance over conventional arrangements. It is known that porous materials in the fin structures increase heat transfer rates along with material consumption reduction through optimized shapes.

Moreover, some coating technologies can also improve the performance by increasing the wettability and corrosion resistance of the surface. Optimization of thermal contact conductance is essential in oscillating systems with variable thermal loads and is minimized by means of specialized coatings that ensure the maximum level of interaction between fin surfaces with working fluids. Material application in the form of oscillating fin design has benefited as a result of the emergence of 3D printing technology. The Powdered Metals for 3D Printing with Superior Flowability class includes metals with good flowability, such as AlSi10Mg, since its Al particles are uniformly sized once powdered for the 3D printing process, and improve the ability to produce intricate geometries that were not possible or even challenging using traditional techniques. These structures operate at high thermal performance under unconjugated operation, and display good dimensional accuracy and uniform surface quality.

Beyond active components, including piezoelectric materials, they are increasingly realized to be an efficient means to further improve heat transfer efficiency. When used with oscillating fins or micro-pin-finned surfaces, these materials can produce synthetic jets or localized agitation within the fluid flow with substantial increases in the convective heat transfer rates. Another promising avenue for future advancements is investigating composite materials. Hybrid structures can be created that utilize the strengths of each component, but mitigate some weaknesses, thus resulting in fins that exhibit improved mechanical performance while mitigating weaknesses still achieving superior thermal performance.

Finally, the innovations in these materials and coatings are necessary to expand the capabilities of oscillating fin technologies. Their ability to improve efficiency without sacrificing durability makes them a critical part of satisfying the increasingly growing requirements that have been put on modern thermal management systems through the various industries [26, 29–33]. Figure 5 shows the SEM images of AlSi10Mg metal powder [9].

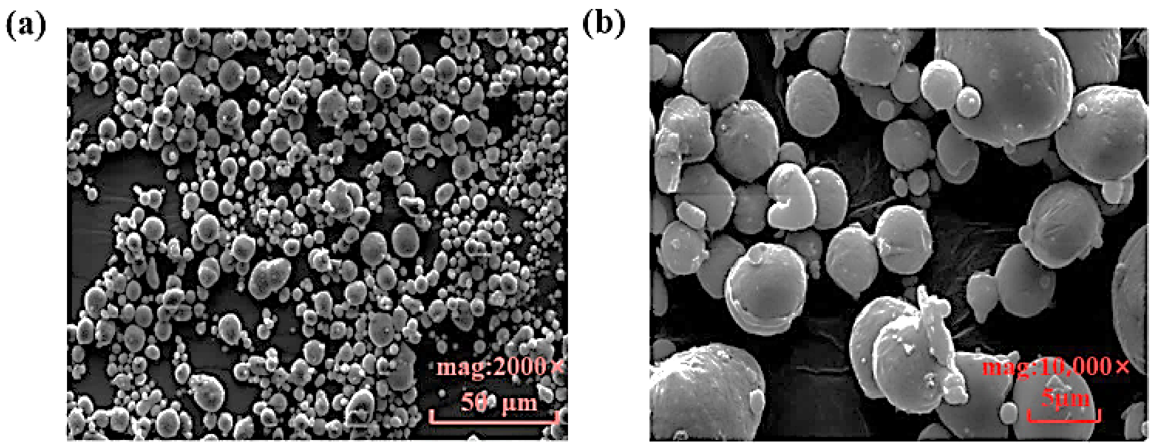


Figure 5. SEM images of AlSi10Mg metal powder: (a) magnified 2000×, (b) magnified 10,000× [9]

5.2 Design Modifications for Enhanced Performance

Oscillating fin heat transfer systems need revisions for better thermal management over their different applications. Current advancement of heat exchange effectiveness in terms of innovative configurations and strategic fin placement is emphasized. Thermal efficiency can be optimized by harnessing the high-velocity airflow in the flow from piezoelectric fans, especially close to fan blades, which can be customized according to the flow patterns. Often, fins are positioned only behind fan blades, where traditional designs fail to capture beneficial proximity airflow. Various flow zone concepts have been used for modern practice, which combines plate and pin fins distributed strategically. By placing plate fins in the parallel flow regions downstream of the blades, these rapid vortices at the blade surface are maintained, increasing heat dissipation rates. Integral pin fins are integrated within vortex-dominated areas to enhance the contact area, yet do not disrupt vortex behavior to improve heat transfer performance.

It is discovered that the optimization outcomes are very sensitive to the properties of the fins. Research has indicated that heat transfer as well as turbulent mixing may be improved with the transition from continuous fin arrays to segmented pin fin designs. The results of this research suggest that a significant difference in performance metrics, such as pressure drop and thermal efficiency, exists, and an elliptical pin structure outperforms a rectangular pin structure by performance per unit of pressure drop.

With additive manufacturing advancements, lighter, customized fins tailored to operational environments can be designed that would better enhance thermal management systems using intricate geometries, which would be difficult to achieve using traditional manufacturing methods like tapered or branched fins. Thermal conductivity and resilience can also be further increased by incorporating advanced materials into the fin designs. Upon the addition of PCMs and inventive fin designs, energy storage capabilities are increased while temperatures remain low, thereby applicable to refrigerated transport.

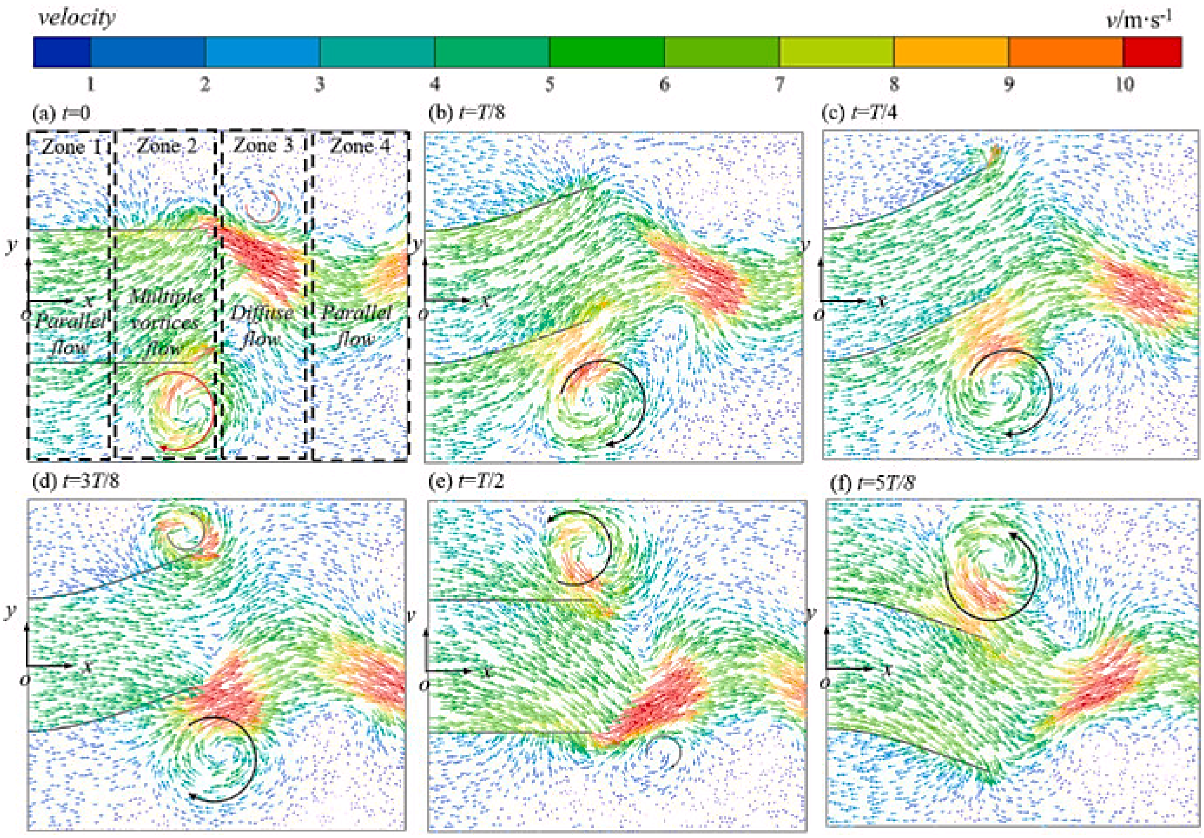


Figure 6. Velocity vector distribution in the channel in one cycle [33]

Design innovation in association with cutting-edge materials and the input from CFD permits systematic refinement of these systems to enhance cooling efficiency, resulting in a more efficient thermal management solution for a wide range of industrial applications [9, 13, 29, 31, 34–36]. Figure 6 shows the velocity vector distribution in the channel in one cycle. Figure 7 shows the schematic diagram of four different fin arrangements of heat sinks. Table 1 shows the dimensionless geometric parameters of four heat sinks with piezoelectric fans (HSPFs) [33]. Figure 8 shows the particle contact time distributions of particle flow around different surfaces under different situations at t = 41 s [13].

Table 1. Dimensionless geometric parameters of four HSPFs [33]

$HSPF_{conv}$		$HSPF_{plate\text{-}pin1}$		$HSPF_{plate\text{-}pin2}$		$HSPF_{inh}$	
L_c^*	22.325	$L_u{}^*$	7.25	$S_2{}^*$	3.5	$S_i{}^*$	2
$S_c{}^*$	2.5	$L_{1,d}{}^*$	16.27	$G_{2'}^*$	1.75	$S_{i'}{}^*$	5.5
G^*	1	$D_p{}^*$	1	$G_2{}^*$	2.59	$S_{i''}*$	6
$W_p{}^*$	1	S^*	1.5	$L_d{}^*$	8.42		
		$G_1{}^*$	14.9				
		$S_1{}^*$	2.5				

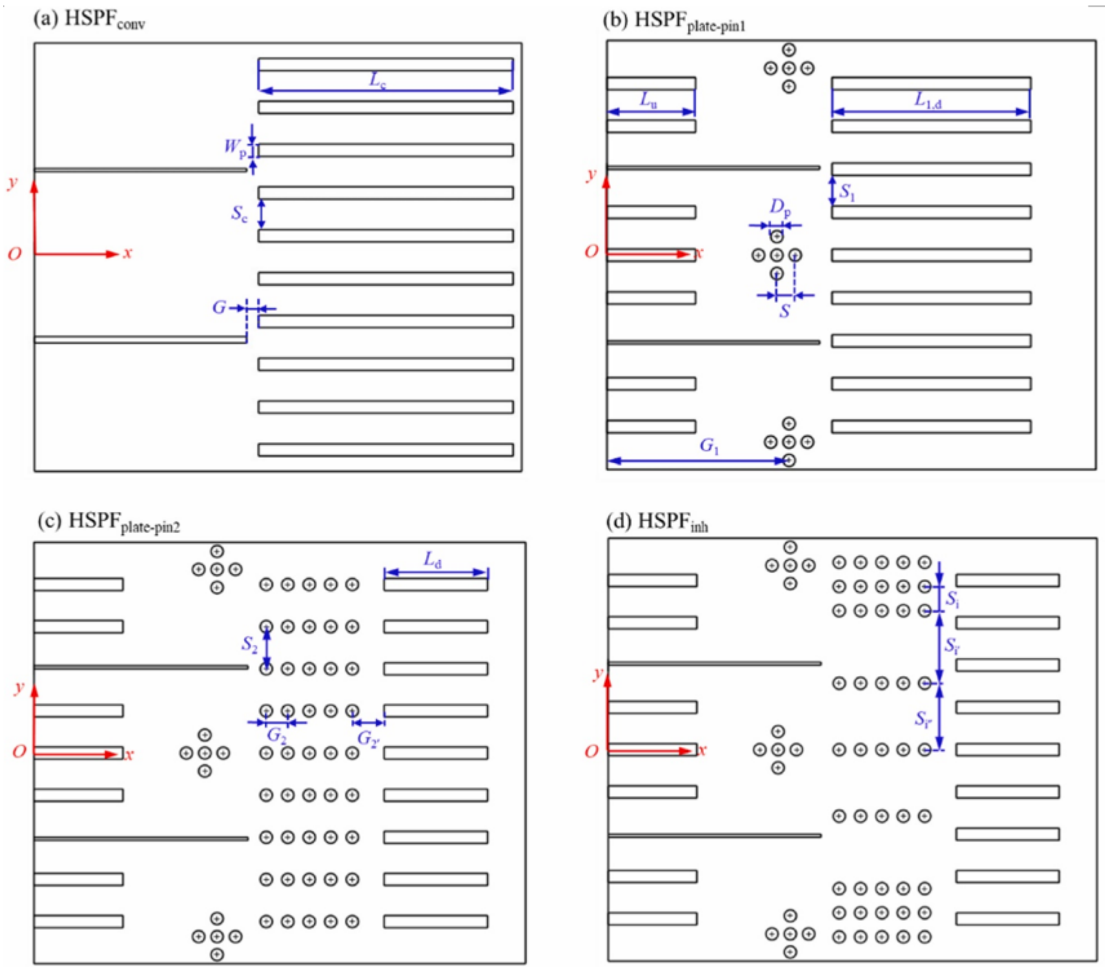


Figure 7. Schematic diagram of four different fin arrangements of heat sinks [34]

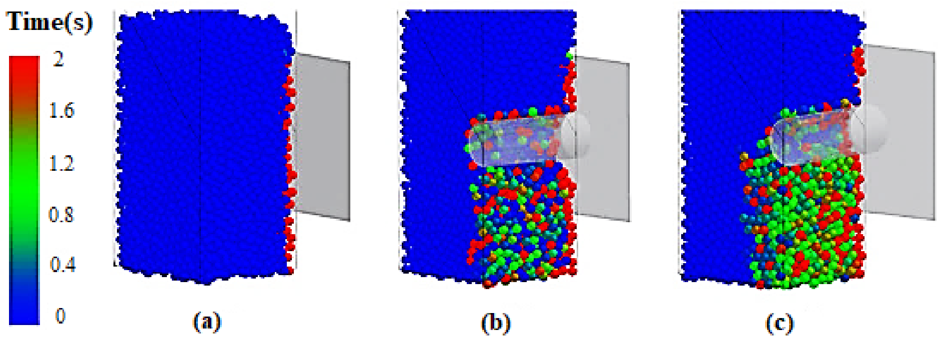


Figure 8. Particle contact time distributions of particle flow around different surfaces under different situations at t = 41 s: (a) Case 1; (b) Case 2; and (c) Case 3 [13]

6 Key Performance Indicators

6.1 Efficiency Metrics in Heat Transfer Applications

The efficiency indicators for heat transfer applications provide an important benchmark in the evaluation of the performance of oscillating fins and their contribution to thermal management systems. The dimensionless parameter that gauges the efficiency of convective heat transfer in relation to conductive processes is the dimensionless Nusselt number (Nu). Better thermal transfer results at higher Nu are often the main point of using oscillating fins. Nu depends on various factors, particularly the characteristics of oscillation such as frequency and amplitude. The research also shows that enhancing Nu can be accomplished by increasing oscillation amplitude, thereby increasing fluid motion as well as disrupting boundary layers that may hinder the transfer of heat. This relates to the fact that, for example, increasing the vibrational frequency up to a defined limit significantly improves results, as shown in some studies; thus, some reports state that Nusselt values increase, for example, up to 20 percent under the best conditions.

In an efficiency sense, the fin designs are very important. Generally, the thin plate fin configurations are more advantageous compared to general designs because they can produce much more potent flow patterns, like the recirculation zones, which enhance thermal interaction between the fluid and the surface areas. Fin characteristics also impact thermal performance under different operational regimes, and it depends on the Reynolds number, a parameter that reflects the flow regime. In addition, by installing these advanced materials in fin designs, their efficiency metrics can be increased. The faster heat transfer rates associated with materials having high thermal conductivity are supported by coatings that reduce fouling or improve wettability, which also contribute to performance indicators. Therefore, it is important to select proper materials when optimizing the oscillating fin designs.

The effectiveness of the oscillating fins is also, in fact, often tested by energy efficiency assessments, and specifically by the analysis of the ratio of useful heat output over energy input. In addition to measuring the thermal performance, this metric also gives an indication of operational sustainability and cost-effectiveness over the entire life cycle of the system. Validation of these efficiency metrics can be done through experimental methods. IR thermography or transient temperature measurement can provide real-time data distribution of temperatures across fins in operation; thus, Nu is determined accurately under different conditions.

In the end, while the numerical simulations offer good insights into the potential heat transfer improvements of oscillations, experimental validations are a must to have confidence in the reliability of the design methodologies. With hybrid systems featuring PCMs or other novel cooling solutions, the need for resilient performance metrics will continue to rise in the face of the increasingly presence of oscillating fins [2, 4, 36–40]. Figure 9 shows the isosurfaces of temperature distribution in the hybrid cooling model with dual PCM and varying fin configurations [36].

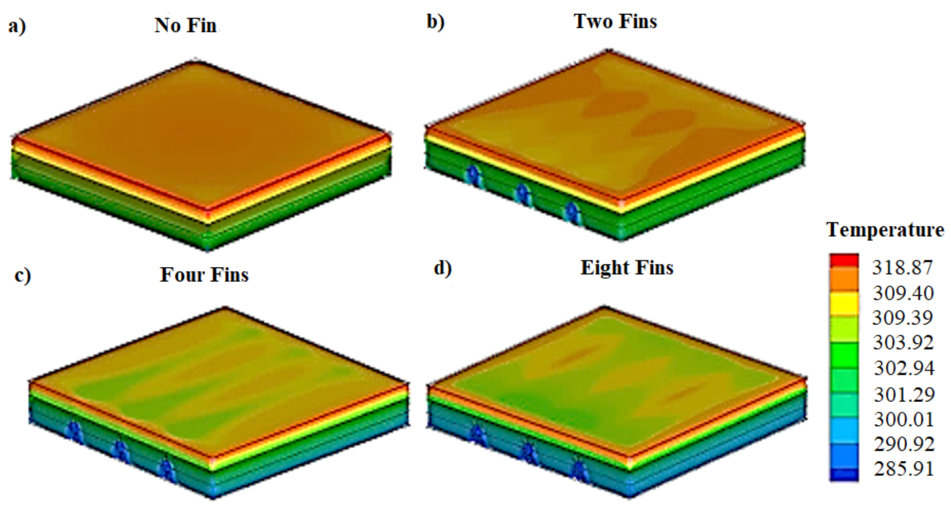


Figure 9. Isosurfaces of temperature distribution in the hybrid cooling model with dual PCM and varying fin configurations [36]

6.2 Durability and Reliability Factors

They are crucial to the effectiveness of the oscillating fin heat transfer systems for long and reliable life. Oscillation reduces thermal resistance but also introduces dynamic forces to the structural components, potentially subjecting them to fatigue or failure. Vibration on material integrity is an important factor for an optimal design. Oscillation frequency may vary considerably during operation. Therefore, the selected materials containing high fatigue resistance are obligatory. The research shows that the higher frequencies increase stress at the fin fluid junctions. By reducing the mass, titanium alloys or composites may replace conventional metals such as aluminum and steel in high-frequency vibration environments. Durability is directly related to the manufacturing methods. All of this can be improved by surface treatments, protective coatings, and additive manufacturing to increase wear and corrosion resistance, respectively. In addition, coatings afford thermal performance benefits by decreasing thermal contact resistance.

This requires reliability assessments under different operational conditions to assure sustained performance. Tests that have covered thermal cycling and mechanical vibrations mimic the real world to find possible failure modes and provide input for modifications to the design prior to deployment. Apart from material selection and testing, durability has to be included in the fin design. The heat transfer should be optimized due to fin geometries that not only maximize heat transfer but also minimize stress concentration in the case of oscillation. Some of the tools used by designers for modeling the effects of dynamic loading scenarios and identifying the points of vulnerability without actually building the prototype include computational techniques, for example, FEA.

Monitoring techniques are also important to be implemented during operation. Structural health sensors that read stress or strain can provide real-time data on system performance, thus allowing the application of predictive maintenance strategies to address wear of components prior to fatigue of the fin system, extending the life of the oscillating fin system.

This is a difficult problem to balance - enhanced heat transfer through oscillation with structural integrity. Studying continuous means of designing advanced materials for use in high-stress applications could lead to a transformation in durability efforts associated with future oscillating applications for heat transfer improvement [3, 13, 41].

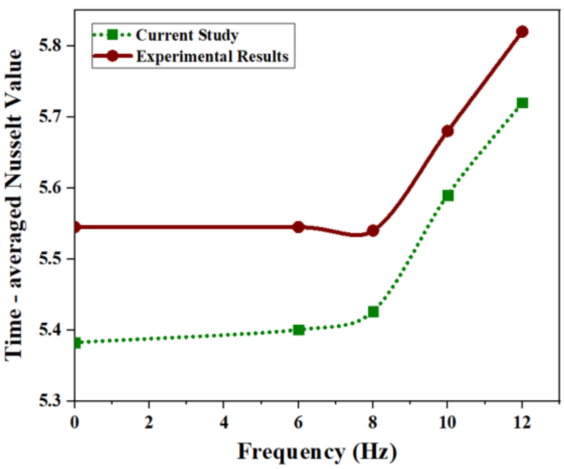
7 Numerical vs. Experimental Results: A Comparative Analysis

The reliability of oscillating fin heat transfer systems has been investigated by considering fine numerical studies and experimental data. CFD models, which can compute the complex fluid dynamics and thermal exchanges in an ideal way, tend to rely on oversimplifying the actual occurrences to solve the problems in a tailored way. Validation of the cell in numerical predictions and the conditions that maintain a gap between numerical predictions and experimental outcomes are indicated in experiments in terms of the amplitude of excitation. Data verifying numerical models are needed as variations are observed in latent versus sensible heat ratios. Experimental measurements of flow behavior and thermal efficiency of the gas turbine are essential to authenticate the CFD results. It has been shown that thermal dynamics in PHPs have been clarified with techniques such as high-speed imaging and IR thermography.

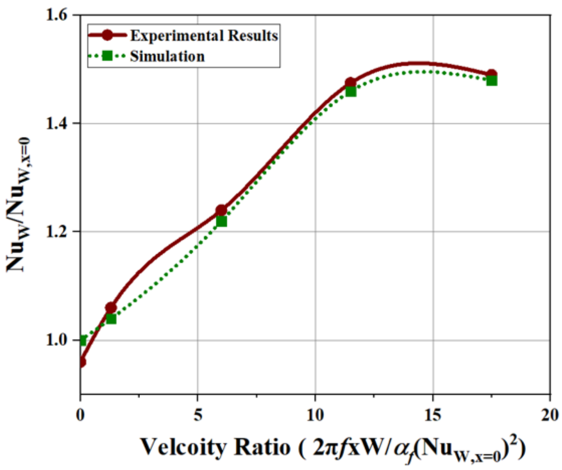
The inclusion of experimental results with numerical simulations improves confidence in understanding oscillating fin performance. Calibrating models on empirical data itself serves as a benchmark of the computational predictions to give a measure of how close computational results lie to their actual behavior. Despite substantial agreement on Nusselt numbers from different approaches, there still exist unresolved problems. Searching for new materials and creative designs leads to new ideas about how vibrations can better increase thermal performance than static configurations. Deviations of 2–3% are typical from validation efforts, which indicate simulations are within 2–3% of actual measurements over configurations. Further experimental studies explore frequency responses in vibration-assisted operations, which in turn affect the fluid properties to generate complex flow patterns that have overall efficiency.

Nevertheless, reliance on theoretical assumptions limits the use of numerical methods; they must always be validated by very special experiments. The results from this comparative analysis show the effectiveness and the accuracy of different modeling strategies and a huge enhancement of the heat transfer coefficient with oscillating fins, despite the fact that measurement uncertainties and other real-world factors tend to cause differences between the simulated and actual performance metrics.

It is important to understand the effect of oscillation frequency on thermal performance, and it may be that conditions found in a simulation are not as optimal in reality. This relationship is further complicated by the interplay between drag reduction and heat transfer, and continuing discussion in a dialogue relationship between numerical and experimental works to further understand the oscillating fin heat transfer systems [2, 4, 23, 42, 43]. Figure 10 shows the validation of this study.



(a)



(b)

Figure 10. Validation of study [4]: (a) Najim et al. [44] validated the traditional heat sink model at an amplitude of 0.005 m; (b) Park et al. [45] validated the thin plate-fin heat sink model at a vibrational frequency of 59 Hz

8 Challenges and Limitations in Oscillating Fin Technology

The theoretical complications and associated practical limitations in the usage of fin technology, including oscillating fins, are varied. The problem is complex fluid dynamics in oscillating systems. The working fluid transitions through phases and bears pressure fluctuations, which have a dynamic behavior to reproduce intricate nonlinear dynamics, creating great difficulty in the modeling and forecasting. This results in limiting their scalability in industrial applications due to the lack of standardized design methodologies. Many of the numerical simulations performed by researchers do not match up with experimental results for various reasons, but few can be attributed to inaccuracies when attempting to quantitatively simulate real-world conditions.

A material challenge is another important limitation. Advanced materials can improve the heat transfer efficiency by a large degree, but at the cost of increased costs or decreased structural integrity when exposed to oscillatory forces. If material fatigue is not prevented, such continuous vibrations will reduce heat transfer performance over the passage of time. In addition, although there are materials that have beneficial thermal properties, the stress produced by oscillation might be harmful or cause a deterioration or failure of such materials.

The design process is made more complex by the inclusion of oscillating fins in existing thermal management systems. It is important to know how the fins interact with other parts to prevent the loss of overall system efficiency. For example, these conventional heat exchangers are not necessarily compatible with oscillating fins because of changes in dynamic flow dynamics and thermal resistance profiles due to changed geometry or flow dynamics. In addition, the experimental methods used to evaluate oscillating fin technologies have not been standardized. There is a general lack of standardization arising from variations in experimental setups, measurement techniques, and instrumentation. This creates a loss of consistency of sources and complicates the reliable performance metrics assessment of different designs or applications.

But economic factors shrink the chances of wide adoption, too. Small investments in research and development are often made before oscillating fin technology can be commercially viable, such as expenses incurred in prototyping and conducting various testing of advanced designs under different operating conditions. The second potential challenge for oscillating fin technologies is the market acceptance, as in general, the industries prefer to use already known solutions if they've been proven reliable, to newer concepts that perhaps have not been shown to be reliable to be use in aerospace or automotive sectors. Indeed, these challenges further highlight the fact that despite apparent promise for significant improvements to the overall heat transfer efficiency, there are substantial barriers to be overcome regarding focused research initiatives that can enable oscillating fin technology to realize its promise in practical applications [4, 23, 30, 34, 46–48].

9 Future Trends and Emerging Technologies

Thermal management systems will be significantly enhanced by several trends and innovations of oscillating fin heat transfer technology as oscillating fin heat transfer technology progresses. Main developments are the use of advanced materials such as metal foams and PCMs to enhance heat transfer performance. Metal foams create turbulence and increase surface area, thereby disrupting the thermal boundary layers for improved performance in heat exchangers. PCMs can also be integrated to store energy during phase changes and in this way be efficient for renewable energy and refrigerated transport.

There is another trend in which the additive manufacturing techniques, such as 3D printing, are being adopted to create complex fin geometries that cannot be created with traditional manufacturing methods. It is possible to customize designs to optimize fluid dynamics and improve oscillation-driven heat transfer, as studies show that 3D printed oscillating finned radiators can considerably decrease thermal resistance instead of a conventional design. A CFD and machine learning combination can very well lead to excellent thermal performance improvement. Machine learning algorithms use extensive datasets from simulations or experiments to analyze the patterns that affect heat transfer, refining the design and designing adaptive control in real time in advanced thermal management systems. It also gets hot applications as it improves the heat transfer efficiency provided by microchannel technology through a high surface area to volume ratio. The oscillation may increase the overall heat transfer rates while these devices promote laminar flow and maximize fluid-surface interactions.

To improve thermal efficiency, surface modification techniques, like texturing or the use of specialized surfaces, try to enhance turbulence in the boundary layer. Other than that, hybrid cooling systems that combine several cooling methodologies, such as those using fins with PCMs, have been studied with the purpose of enhancing energy storage capabilities of electric vehicles and high-performance electronics.

Finally, it can be concluded that future trends related to oscillating fin heat transfer technology will integrate computational methods, materials, manufacturability, and cooling integrated solutions, and are expected to result in significant improvements in efficiency in various applications [31, 33, 36, 42, 49].

10 Conclusion

It is shown that the investigation into thermal performance enhancement through oscillating fin technology provides insight into improvements that can be made for thermal performance across a range of engineering problems. Advancing materials are also key to heat transfer rates through interaction with oscillation. The results of research show that convective heat transfer can be enhanced due to fluid motion accompanied by fin oscillating action that can disrupt the thermal boundary layer and provide efficient heat dissipation. Such an effect is especially noticeable when working with flexible fins, which conform to the fluid flow dynamics and therefore decrease the stagnation zones, leaving a more uniform temperature distribution.

The use of numerical methods such as CFD and FEA has further helped us to accurately model such complex oscillating systems. The parameter optimization offered by these methods is thus made possible, both with respect to parameters like frequency, amplitude, or material properties. Therefore, thermal efficiency could be improved and energy consumption minimized. Regardless of how the methods are combined, it was found that compared to the use of any other conventional static elements, oscillating fins work much better when the design is well chosen. To advance this field, there is an ongoing advancement of experimental methodologies. Researchers have been able to gather true data on the heat transfer characteristics in various conditions using sophisticated measurement tools and innovative laboratory setups. The data is an empirical example that a theoretical model can be built upon and applied in many different areas of people's lives in electronics, renewable energy, manufacturing, and many other sectors.

There are also some innovations in fin design which should be noticed, especially in recent years when there is increasing interest in developing active and passive heat transfer management strategy integration. In fact, an example of such an application is the case of slotted fins, which have both benefits, i.e., heat transfer enhancement and reduction in drag coefficients in turbulent flows. For real-world situations where both thermal and mechanical strength are important, such optimizations are required. There are, however, challenges in this field. Current issues include material fatigue as a result of continuous oscillation cycles, as well as manufacturing restrictions imposed by the demands of analytically complex geometries. Furthermore, although engineers have to continue trying to achieve high enough performance levels with minimal costs and without the complication of maintenance, they do this.

Future trends relating to the use of oscillating fin technology look promising, with breakthroughs predicted by the creation of new materials such as smart alloys or phase-change materials, whose properties depend on environmental conditions. These types of innovations can revolutionize the industry of thermal solutions management. Overall, deep improvement of the heat transfer across various applications may then be achieved by deepening our understanding of oscillating fin systems [2, 12, 18, 23, 36, 48–50].

The latest achievements and remaining issues in oscillating fin technology used for thermal control have been summarized. Important advancements made involve optimizing the movement of the fin, picking hardy composite materials and coatings to improve its sustainability, and exploiting 3D printing to create advanced lightweight fins without majorly increasing costs. Adding components like piezoelectric materials into engine components can offer attractive prospects for fin oscillation control.

A combination of CFD, FETA, and prime tests allows engineers to improve their designs and explore how fluid flows around moving fins. By using this two-way process, approaches can be developed to improve materials, designs, and actions used in manufacturing for better results.

This study suggests that for future growth, vibrating fin technology should mainly focus on producing vibrating fins in large numbers, checking durability while under regular operations, and including piezoelectric actuators and other multipurpose composites. The improvements will make it possible to use oscillating fin technology reliably and affordably in electronics cooling, the automotive sector, and renewable energy. The information and advice in this review help guide researchers and engineers to more readily and successfully introduce oscillating fins in new high-efficiency products.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] S. A. Bonab, F. M. Osalu, and M. Goharkhah, "Application of oscillating elastic surfaces for heat transfer enhancement from heat dissipating electronic chips," *Int. Commun. Heat Mass Transf.*, vol. 159, p. 108163, 2024. https://doi.org/10.1016/j.icheatmasstransfer.2024.108163

[2] H. Soheibi, Z. Shomali, and J. Ghazanfarian, "Combined active-passive heat transfer control using slotted fins and oscillation: The cases of single cylinder and tube bank," *Int. J. Heat Mass Transf.*, vol. 182, p. 121972, 2022. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121972

[3] L. Li, X. Sun, H. Kang, and Y. Wang, “Influence of vibration parameters and fin structure parameters on heat transfer performance under vibration conditions,” *Case Stud. Therm. Eng.*, vol. 57, p. 104311, 2024. https://doi.org/10.1016/j.csite.2024.104311

[4] A. H. D. K. Rasangika, M. S. Nasif, and R. Al-Waked, “Comparison of forced convective heat-transfer enhancement of conventional and thin plate-fin heat sinks under sinusoidal vibration,” *Appl. Sci.*, vol. 13, no. 21, p. 11909, 2023. https://doi.org/10.3390/app132111909

[5] S. U. Khalid and M. A. Nasir, “Evaluation of innovative thermal performance augmentation techniques in heat sinks & heat pipes: Electronics & renewable energy applications,” *Int. J. Heat Fluid Flow*, vol. 108, p. 109490, 2024. https://doi.org/10.1016/j.ijheatfluidflow.2024.109490

[6] A. Rahman and D. Tafti, “Characterization of heat transfer enhancement for an oscillating flat plate-fin,” *Int. J. Heat Mass Transf.*, vol. 147, p. 119001, 2020. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119001

[7] X. Luo, W. Zhang, H. Dong, A. K. Thakur, B. Yang, and W. Zhao, “Numerical analysis of heat transfer enhancement of fluid past an oscillating circular cylinder in laminar flow regime,” *Prog. Nucl. Energy*, vol. 139, p. 103853, 2021. https://doi.org/10.1016/j.pnucene.2021.103853

[8] F. H. M. Ali, E. F. Abbas, I. J. Hasan, and S. M. Fakhraldin, “Using mechanical vibration to enhance heat transfer on an extended surface: A review study,” *Am. J. Sci. Eng. Technol.*, vol. 8, no. 3, pp. 162–172, 2023. https://doi.org/10.11648/j.ajset.20230803.16

[9] X. Xiao, Y. He, Q. Wang, Y. Yang, C. Chang, and Y. L. Ji, “Heat transfer performance of a 3D-printed aluminum flat-plate oscillating heat pipe finned radiator,” *Nanomaterials*, vol. 14, no. 1, p. 60, 2023. https://doi.org/10.3390/nano14010060

[10] H. Baker, J. McDonough, and R. Law, “Enhancing heat transfer in micro pin fin heat sinks using flow oscillations,” in *Proceedings of the 18th UK Heat Transfer Conference, Birmingham*, 2024. https://more.bham.ac.uk/ukhtc-2024/wp-content/uploads/sites/80/2024/09/UKHTC-2024_paper_149.pdf

[11] E. Jamesahar, M. Sabour, M. Shahabadi, S. A. M. Mehryan, and M. Ghalambaz, “Mixed convection heat transfer by nanofluids in a cavity with two oscillating flexible fins: A fluid-structure interaction approach,” *Appl. Math. Model.*, vol. 82, pp. 72–90, 2020. https://doi.org/10.1016/j.apm.2019.12.018

[12] A. R. Barandagh, A. R. Barandagh, and J. Ghazanfarian, “Combined active-passive heat transfer enhancement for a partial superhydrophobic oscillating cylinder,” *arXiv preprint*, 2022. https://arxiv.org/abs/2203.02265

[13] X. Tian, J. Yang, Z. Guo, and Q. Wang, “Numerical investigation of gravity-driven granular flow around the vertical plate: Effect of pin-fin and oscillation on the heat transfer,” *Energies*, vol. 14, no. 8, p. 2187, 2021. https://doi.org/10.3390/en14082187

[14] M. Ghalambaz, E. Jamesahar, M. A. Ismael, and A. J. Chamkha, “Fluid-structure interaction study of natural convection heat transfer over a flexible oscillating fin in a square cavity,” *Int. J. Therm. Sci.*, vol. 111, pp. 256–273, 2017. https://doi.org/10.1016/j.ijthermalsci.2016.09.001

[15] K. Zhang, Y. Zhang, X. Wang, and L. Wang, “Effect of fin number and position on non-linear characteristics of natural convection heat transfer in internally finned horizontal annulus,” *Front. Energy Res.*, vol. 9, p. 804094, 2021. https://doi.org/10.3389/fenrg.2021.804094

[16] A. A. A. Obaid, S. E. Razavi, and F. Talati, “Numerical investigation of flow inside a channel with elastic vortex generator and elastic wall for heat transfer enhancement,” *J. Appl. Fluid Mech.*, vol. 17, no. 11, pp. 2377–2389, 2023. https://doi.org/10.47176/jafm.17.11.2601

[17] A. Azrz and T. Y. NA, “Periodic heat transfer in fins with variable thermal parameters,” *Int. J. Heat Mass Transf.*, vol. 24, no. 8, pp. 1397–1404, 1981.

[18] X. Sun, Z. Ye, J. Li, K. Wen, and H. Tian, “Forced convection heat transfer from a circular cylinder with a flexible fin,” *Int. J. Heat Mass Transf.*, vol. 128, pp. 319–334, 2019. https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.123

[19] A. R. A. Khaled, “Thermal characterizations of exponential fin systems,” *Math. Probl. Eng.*, vol. 2010, p. 765729, 2010. https://doi.org/10.1155/2010/765729

[20] S. A. Al-Sanea and A. A. Mujahid, “A numerical study of the thermal performance of fins with time-dependent boundary conditions, including initial transient effects,” *Wärme - und Stoffübertragung*, vol. 28, pp. 417–424, 1993. https://doi.org/10.1007/BF01577883

[21] M. H. M. Al-Ezzi, S. E. Razavi, and F. Talati, “Integration of fluid-structure interaction with natural convection in a cavity featuring a heated cylinder with periodic heat flux alongside flexible oscillating fins,” Preprint, 2023. https://ssrn.com/abstract=5200521

[22] C. Jung and S. J. Kim, “Effects of oscillation amplitudes on heat transfer mechanisms of pulsating heat pipes,” *Int. J. Heat Mass Transf.*, vol. 165, p. 120642, 2021. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120642

[23] A. Winarta, N. Putra, R. A. Koestoer, A. S. Pamitran, and I. I. Hakim, “Heat transfer performance of oscillating heat pipe with ethanol and methanol working fluid with different inclinations for heat recovery application,” *J.*

Adv. Res. Fluid Mech. Therm. Sci., vol. 57, no. 2, pp. 148–157, 2019.

[24] A. Piccolo, R. Siclari, F. Rando, and M. Cannistraro, “Comparative performance of thermoacoustic heat exchangers with different pore geometries in oscillatory flow. implementation of experimental techniques,” *Appl. Sci.*, vol. 7, no. 8, p. 784, 2017. https://doi.org/10.3390/app7080784

[25] M. Machesa, L. Tartibu, and M. Okwu, “Prediction of the oscillatory heat transfer coefficient in thermoacoustic refrigerators,” *Sustainability*, vol. 13, no. 17, p. 9509, 2021. https://doi.org/10.3390/su13179509

[26] A. Hamood, A. J. Jaworski, L. Blunt, and A. Townsend, “The application of additive manufacturing to heat exchangers for oscillatory flow: A case study,” *J. Eng. Manuf.*, vol. 238, no. 10, pp. 1531–1540, 2023. https://doi.org/10.1177/09544054231199520

[27] S. A. Niknam, M. Mortazavi, and D. Li, “Additively manufactured heat exchangers: A review on opportunities and challenges,” *Int. J. Adv. Manuf. Technol.*, vol. 112, no. 3, pp. 601–618, 2021. https://doi.org/10.1007/s00170-020-06372-w

[28] T. Deshamukhya, D. Bhanja, and S. Nath, “Heat transfer enhancement through porous fins: A comprehensive review of recent developments and innovations,” *J. Mech. Eng. Sci.*, vol. 235, no. 5, pp. 946–960, 2020. https://doi.org/10.1177/0954406220939600

[29] B. Anwajler, “Potential of 3D printing for heat exchanger heat transfer optimization—sustainability perspective,” *Inventions*, vol. 9, no. 3, p. 60, 2024. https://doi.org/10.3390/inventions9030060

[30] T. Yeom, T. Simon, M. Zhang, Y. Yu, and T. Cui, “Active heat sink with piezoelectric translational agitators, piezoelectric synthetic jets, and micro pin fin arrays,” *Exp. Therm. Fluid Sci.*, vol. 99, pp. 190–199, 2018. https://doi.org/10.1016/j.expthermflusci.2018.07.035

[31] S. T. W. Kuruneru, K. Vafai, E. Sauret, and Y. Gu, “Application of porous metal foam heat exchangers and the implications of particulate fouling for energy-intensive industries,” *Chem. Eng. Sci.*, vol. 228, p. 115968, 2020. https://doi.org/10.1016/j.ces.2020.115968

[32] G. Mahajan, H. Cho, A. Smith, and S. M. Thompson, “Experimental analysis of atypically long finned oscillating heat pipe for ventilation waste heat recovery application,” *J. Therm. Sci.*, vol. 29, pp. 667–675, 2020. https://doi.org/10.1007/s11630-019-1178-5

[33] C. Han, X. Ma, and J. L. Xu, “Innovative configurations for heat sink integrated with piezoelectric fans,” *Int. J. Therm. Sci.*, vol. 207, p. 109383, 2025. https://doi.org/10.1016/j.ijthermalsci.2024.109383

[34] S. Hosseini, S. Aghebatandish, A. Dadvand, and B. C. Khoo, “An immersed boundary-lattice boltzmann method with multi relaxation time for solving flow-induced vibrations of an elastic vortex generator and its effect on heat transfer and mixing,” *Chem. Eng. J.*, vol. 405, p. 126652, 2021. https://doi.org/10.1016/j.cej.2020.126652

[35] Y. Yang, Z. Wang, H. Ayed, and J. Alhoee, “Incorporating nickel foam with nano-encapsulated phase change material and water emulsion for battery thermal management: Coupling CFD and machine learning,” *Case Stud. Therm. Eng.*, vol. 60, p. 104672, 2024. https://doi.org/10.1016/j.csite.2024.104672

[36] N. C. DeJong and A. M. Jacobi, “An experimental study of flow and heat transfer in offset strip and louvered-fin heat exchangers,” Air Conditioning and Refrigeration Center, TR-91, 1995. https://www.ideals.illinois.edu/items/11166

[37] M. A. Alomari, A. M. Hassan, A. Alajmi, A. M. Sadeq, F. Alqurashi, and M. A. Flayyih, “A comprehensive numerical analysis of heat transfer enhancement in NEPCM-water mixtures using oscillating fin and oriented magnetic fields,” *Int. Commun. Heat Mass Transf.*, vol. 161, p. 108455, 2025. https://doi.org/10.1016/j.icheatmasstransfer.2024.108455

[38] A. Das, F. T. Mahmood, R. B. Smriti, S. Saha, and M. N. Hasan, “CFD analysis of heat transfer enhancement by wall mounted flexible flow modulators in a channel with pulsatile flow,” *Heliyon*, vol. 9, no. 6, p. e16741, 2023. https://doi.org/10.1016/j.heliyon.2023.e16741

[39] A. H. D. K. Rasangika, M. S. Nasif, W. Pao, and R. Al-Waked, “Numerical investigation of the effect of square and sinusoidal waves vibration parameters on heat sink forced convective heat transfer enhancement,” *Appl. Sci.*, vol. 12, no. 10, p. 4911, 2022. https://doi.org/10.3390/app12104911

[40] Y. T. Yang and M. L. Hwang, “Numerical simulation of turbulent fluid flow and heat transfer characteristics in heat exchangers fitted with porous media,” *Int. J. Heat Mass Transf.*, vol. 52, no. 13–14, pp. 2956–2965, 2009. https://doi.org/10.1016/j.ijheatmasstransfer.2009.02.024

[41] B. Lotfi and B. Sundén, “Thermo-hydraulic performance enhancement of finned elliptical tube heat exchangers by utilizing innovative dimple turbulators,” *Heat Transf. Eng.*, vol. 41, no. 13, pp. 1117–1142, 2019. https://doi.org/10.1080/01457632.2019.1611132

[42] J. Y. Ho, K. C. Leong, and T. N. Wong, “Experimental and numerical investigation of forced convection heat transfer in porous lattice structures produced by selective laser melting,” *Int. J. Therm. Sci.*, vol. 137, pp. 276–287, 2019. https://doi.org/10.1016/j.ijthermalsci.2018.11.022

[43] M. Alarcón, F. Alhama, and C. F. González-Fernández, “Transient conduction in a fin-wall assembly with

harmonic excitation–network thermal admittance," *Heat Transf. Eng.*, vol. 23, no. 2, pp. 31–43, 2002. https://doi.org/10.1080/01457630252800412

[44] R. Najim, J. H. Wahib, S. M. Jalil, and M. Ibrahim, "Experimental study of the effect of vertical oscillation on forced convection coefficient from vertical channel," *Anbar J. Eng. Sci.*, vol. 2013, pp. 1–13, 2013.

[45] K. T. Park, J. W. Lee, M. G. Lee, H. J. Kim, and D. K. Kim, "Nusselt number correlation for vibration-assisted convection from vertically oriented plate fins," *Int. J. Heat Mass Transf.*, vol. 78, pp. 522–526, 2014. https://doi.org/10.1016/j.ijheatmasstransfer.2014.07.015

[46] L. Dai, X. Wu, Y. Guo, H. Hou, Z. Hu, Y. Lin, and Z. Yuan, "An enhanced heat transfer method based on the electrocapillary effect of gallium-based liquid metal," *Lab Chip*, vol. 24, no. 24, pp. 5318–5327, 2024. https://doi.org/10.1039/d4lc00791c

[47] M. A. Rahman, S. M. M. Hasnain, P. Paramasivam, and A. G. Ayanie, "Advancing thermal management in electronics: A review of innovative heat sink designs and optimization techniques," *RSC Adv.*, vol. 14, pp. 31 291–31 319, 2024. https://doi.org/10.1039/D4RA05845C

[48] Z. Y. Wang, Z. Q. Huang, T. Li, S. Wang, G. Li, and Z. Chen, "Heat transfer characteristics and deformation effects of compressor air-cooled cylinder based on heat-flow-solid coupling," *Appl. Therm. Eng.*, vol. 228, p. 120395, 2023. https://doi.org/10.1016/j.applthermaleng.2023.120395

[49] K. A. Abro, Q. M. Al-Mdallal, and I. Q. Memon, "Sinusoidal heating on convective heat transfer of nanofluid under differential technique," *ZAMM*, vol. 104, p. e202300895, 2024. https://doi.org/10.1002/zamm.202300895

[50] X. Zhao, Y. Zhu, and H. Li, "Micro-channel oscillating heat pipe energy conversion approach of battery heat dissipation improvement: A review," *Energies*, vol. 15, p. 7391, 2022. https://doi.org/10.3390/en15197391