CURRENT PARADIGMS IN TRIBOLOGY AND MECHANICAL VENTILATION SYSTEMS

Editor

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CURRENT PARADIGMS IN FRICTION, WEAR, AND LUBRICATION SCIENCE

HAKAN ADATEPE[1]

Introduction

This chapter thoroughly reviews the development of friction, wear, and lubrication science over the past 20 years, focusing on how it affects mechanical engineering design. While traditional concepts like Coulomb's friction laws and Archard's wear equation are still important, they are now expanded by contact mechanics, nanotribology, tribochemistry, green tribology, and data-focused triboinformatics methods.

The chapter starts by outlining the shift from basic empirical friction laws to models that explicitly incorporate surface topography and multiscale contact. It then explores system-level and life-cycle approaches where enhancing energy efficiency and sustainability has become a central focus. Later sections highlight progress in nanometer-scale experiments and simulations, advancements in biotribology and biomimetic surfaces, and the growing influence of machine learning and digital twins in

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predictive tribology. The chapter concludes by summarizing key design insights for mechanical engineers and identifying promising directions for future research.

The Importance of Tribology in Engineering

Tribology is the scientific discipline that studies the interaction of surfaces in relative motion, focusing on the phenomena of friction, wear, and lubrication (Bhushan, 2013a; Stachowiak & Batchelor, 2014). While this definition is succinct, the implications of tribological processes on both economic and technological aspects are profound. According to global assessments, the economic losses attributed to friction and wear in mechanical systems account for a significant portion of national income in many industrialized nations (Holmberg & Erdemir, 2017). As a result, even incremental improvements in tribological performance can have a far-reaching impact on energy efficiency, the longevity of components, maintenance costs, and, ultimately, sustainability.

Historically, the field of tribology has evolved primarily through empirical and experimental approaches. Bowden and Tabor's seminal work (1950) established a connection between macroscopic frictional forces and the real contact area between surfaces, marking a shift from phenomenological models to a more comprehensive theoretical framework. Later contributions by Bhushan (2013a, 2013b) and Stachowiak & Batchelor (2014) were pivotal in formalizing the field of "engineering tribology," incorporating principles of contact mechanics, surface characterization, and lubrication into an integrated design approach.

In the past decade or so, tribology has experienced a transformative shift. Advancements in surface metrology, scanning probe microscopy, in-situ microscopy, multiscale simulations, and data analytics have significantly enhanced our understanding of tribological behavior. This has been further catalyzed by societal demands for low-carbon, resource-efficient technologies. Recent comprehensive reviews, such as those by Meng et al. (2022) covering tribological developments from 2020 to 2021, emphasize the rising importance of specialized areas such as nanotribology, biotribology, tribology in extreme environments, and computationally intensive approaches. These emerging fields represent the forefront of tribological research and are reshaping the future of engineering practices.

Paradigms and Paradigm Shifts in Tribology

In the philosophy of science, a paradigm refers to a set of common concepts, assumptions, and methods that structure research within a field. In tribology, paradigms are reflected in how surfaces are idealized (smooth vs. rough, deterministic vs. statistical), how contact is modeled (uniform vs. highly localized), and which mechanisms are considered dominant in friction and wear. Paradigm shifts occur when these assumptions are revisited in light of new evidence, tools, or societal demands.

Three key trends that characterize current tribological paradigms can be summarized as follows:

Multiscale Thinking: Tribological behavior is now analyzed across a wide range of length scales, from atomic and molecular interactions to macroscopic contact regions (Bhushan, 2013b; Malav & Tyagi, 2019; Meng et al., 2022).

System-Level and Life-Cycle Approaches: Tribological decisions are increasingly evaluated not in isolation but in terms of their impact on system efficiency, environmental footprint, and life-cycle cost; this approach forms the core of green tribology (Holmberg & Erdemir, 2017; Nosonovsky & Bhushan, 2012, 2013).

Integration of Experimentation, Modeling, and Data: There is a clear trend toward integrating tribometric experiments, numerical simulations, and machine learning models in predictive and optimized frameworks, often referred to as triboinformatics (Sose et al., 2023; Zahoor et al., 2025).

The following sections explore how these trends manifest in the science of friction (Section 2), wear (Section 3), and lubrication (Section 4), and their interconnections with nanotribology (Section 5), biotribology (Section 6), system-level and digital tribology (Sections 7–8). Section 9 summarizes design implications, and Section 10 outlines future research directions.

Current Paradigms in Friction Science

From Coulomb Friction to State-Dependent Friction

At an introductory level, friction is often described by Coulomb-Amontons' laws:

$$F_f=\mu N$$

with (F_f) the friction force (N) the normal load and (μ) the coefficient of friction. These expressions assume that friction is independent of the nominal contact area and that (μ) is a constant determined solely by the material pair (Stachowiak & Batchelor, 2014). Their surprising success in many basic design calculations explains their widespread use in engineering applications.

However, Bowden and Tabor's (1950) work demonstrated that friction in metallic contacts is better understood in terms of the real contact area and the shear resistance of asperity bonds. Subsequent studies have shown that the friction coefficient is significantly influenced by sliding velocity, contact temperature, surface topography, third-body particles, lubrication regimes, and tribochemical reactions (Bhushan, 2013b; Meng et al., 2022).

As a result, modern tribology treats the friction coefficient not as a constant material property, but as a state-dependent quantity that reflects the instantaneous conditions of the tribosystem. This perspective aligns with rate-and-state friction laws used in seismology and geomechanics and is increasingly adopted in mechanical engineering contexts.

Surface Topography and Multiscale Contact

A second key development pertains to how surfaces are represented. Rather than being defined by a single scale of roughness (e.g., arithmetic average roughness), surfaces are modeled as multiscale topographies exhibiting roughness over a broad range of wavelengths and orientations (Bhushan, 2013b; Stachowiak & Batchelor, 2014). Fractal or self-affine representations are commonly used to capture this behavior.

Multiscale contact models derived from this framework highlight the following:

Only a small portion of the nominal contact area carries load at any given time.As asperities elastically and plastically deform and fracture, the real contact area changes over time.

Local contact conditions at micro and nano scales (stress, temperature, adhesion) strongly influence the macroscopic friction coefficient and wear rate.

To model these effects, analytical models such as Greenwood-Williamson are combined with finite element, boundary element, and discrete element methods, allowing for the numerical prediction of real contact area, local stress distributions, and interface shear stresses under realistic loading and environmental conditions (Bhushan, 2013a; Meng et al., 2022).

Within this paradigm, surface texturing has emerged as an important design strategy. Surface patterns such as dimples, grooves, and pockets can serve as micro-reservoirs for lubricants, enhance hydrodynamic lifting forces, or control directional friction. Recent studies have used machine learning to explore the vast design space of texture parameters, optimizing them for multiple objectives (Ge et al., 2024).

Nanoscale Friction and Nanotribology

Nanotribology has opened a new window into friction at very small length scales. Lateral force microscopy (LFM) used in atomic force microscopes (AFM) and atomistic resolution molecular dynamics (MD) simulations have been particularly effective (Bhushan, 2013b; Malav & Tyagi, 2019).

Some widely accepted findings in nanotribology include: Friction at the nanoscale is often observed as stick-slip behavior, which arises from the system hopping between metastable positions on a complex potential energy surface.

The magnitude and even the qualitative form of friction can be strongly influenced by atomic-scale details such as lattice matching, surface defects, and adsorbed layers (Bhushan, 2013b; Malav & Tyagi, 2019).

Layered and two-dimensional materials, such as graphene and MoS_2, can exhibit superlubricity regimes where friction is orders of magnitude lower than with traditional materials (Bhushan, 2013a; Meng et al., 2022).

These findings demonstrate that macroscopic friction is an emergent property resulting from the collective effects of numerous microscopic events. Moreover, these studies directly impact surface engineering applications, especially in micro/nano-electromechanical systems and high-performance coatings (Bhushan, 2013a; Nasser et al., 2024).

Thermodynamic and Entropy-Based Approaches

A more recent conceptual trend is the application of disequilibrium thermodynamics to friction and wear. In this approach, the question is no longer just how much mechanical work is converted into heat, microstructural changes, and chemical transformations, but how these relate to entropy production (Meng et al., 2022; Zahoor et al., 2025).

In this framework:

The friction coefficient can be interpreted as a measure of the irreversibly dissipated portion of the input power.

Wear processes can be associated with local entropy production, allowing for comparisons between different mechanisms.

Tribological design becomes a problem of controlling the paths of energy dissipation and limiting harmful energy concentrations.

Though still under development, these thermodynamic approaches offer a promising pathway for formulating more general wear criteria that do not rely on a single dominant mechanism.

Data-Driven Friction Modeling and Triboinformatics

Finally, data-driven methods are starting to reshape friction research. Today, tribological experiments often generate large data sets, and numerical simulations further increase the volume of available data. Machine learning provides tools to extract patterns from these data and develop predictive models (Sose et al., 2023).

Typical applications include:

Regression models that predict friction coefficients, wear volumes, or temperatures from tribometer inputs such as load, speed, roughness, and lubricant formulation (Roslan et al., 2025; Sose et al., 2023).

Surrogate models using artificial neural networks for complex numerical models, enabling the multi-objective optimization of surface textures and operating conditions (Ge et al., 2024).

Data-driven materials discovery studies that identify candidate coatings, alloys, or composites with predicted tribological performance (Zahoor et al., 2025).

These types of studies are increasingly being integrated with curated tribological databases and advanced analysis techniques, collectively referred to as triboinformatics. The long-term goal is to make tribological behavior more predictable and accelerate the discovery of high-performance tribosystems (Zahoor et al., 2025).

Current Paradigms in Wear Science

Archard's Law and Its Generalization

At the macroscopic scale, wear is often approximated by Archard's law:

$$V=\mu k\, WL/H$$

in which (V) is the wear volume, (W) the normal load, (L) the sliding distance, (H) the hardness of the softer body, and (k) a non-dimensional wear coefficient (Stachowiak & Batchelor, 2014).). This expression is simple, transparent, and quite useful for many engineering estimates.

However, it is well known today that the Archard coefficient (k) includes the total effect of processes such as adhesion, abrasive, oxidative, fatigue, and tribochemical wear. It does not explicitly account for the influence of third-body particles, evolving surface topography, or changes in lubrication regimes (Stachowiak &

Batchelor, 2014; Meng et al., 2022). Consequently, in current research, (k) is often treated as an effective, state-dependent parameter that varies with contact pressure, sliding speed, temperature, environment, and surface condition, evolving to reflect regimes such as break-in, steady-state operation, and pre-failure stages over time.

Wear Mechanism Maps and Multimodal Wear

Wear-mechanism maps, developed and popularized by Stachowiak and Batchelor (2014), offer a structured way to visualize which wear types dominate under specific load, speed, and environmental conditions. These maps are valuable for both interpreting experimental data and guiding design decisions.

Recent studies emphasize that real tribosystems often operate in regions where multiple mechanisms are simultaneously active. For instance, adhesion, oxidation, and three-body abrasive wear may contribute concurrently and at varying rates to overall wear. Microstructural features such as grain size, second-phase particles, and residual stresses can strongly influence transitions between mechanisms (Bhushan, 2013a; Meng et al., 2022).

At the nanoscale, reviews by Malav & Tyagi (2019) and Sadeghi et al. (2024) show that wear processes may involve the phase transformation and reorganization of just a few atomic layers, requiring conceptual tools beyond classical volumetric wear models.

Surface Evolution and Functional Surfaces

Viewing wear as part of a broader surface evolution process is a useful conceptual step. Under repeated loading and sliding, surfaces alter their topography, chemistry, and subsurface microstructure, which strongly influences subsequent friction and wear. This perspective naturally leads to the concept of functional surfaces, which are intentionally designed to provide specific tribological behaviors (e.g., low friction, high wear resistance, specific wettability) through specific geometric and material properties (Bhushan, 2013a; Stachowiak & Batchelor, 2014). Examples include:

Laser-textured surfaces that generate hydrodynamic lifting forces or trap particles, Diffusion layers and hard coatings that enhance wear and fatigue resistance (e.g., nitrided or carburized layers, DLC films),

Surfaces that promote stable tribofilms under operating conditions, providing self-protection to the base material (Meng et al., 2022; Nasser et al., 2024)

These types of surfaces are increasingly becoming integral components of engineering design, no longer seen merely as by-products of the manufacturing process.

Multiscale Modeling for Wear and Digital Twins

Wear research is becoming increasingly integrated with multiscale modeling. Molecular dynamics simulations at the atomic scale can reveal the early stages of bond breaking and defect formation. At the microstructural scale, finite element and discrete element models are used to simulate crack initiation, crack propagation, and particle detachment. At the component and system level, contact forces, stress fields, and temperature distributions in complex assemblies like gears, bearings, and rail-wheel contacts are predicted (Meng et al., 2022).

The concept of digital twins extends these tools by linking them with real-time usage data. By leveraging sensor information such as vibration signatures, temperature, acoustic emissions, and lubricant condition, the virtual representation of a system can be continuously updated, enabling the prediction of wear conditions and remaining useful life (Zahoor et al., 2025). This approach is especially attractive for safety-critical and capital-intensive assets.

Current Paradigms in Lubrication Science

Elastohydrodynamic Lubrication and Micro-EHL

Lubrication theory has significantly evolved beyond classical hydrodynamic models for smooth surfaces and Newtonian fluids. In concentrated, highly loaded contacts such as gears and rolling element bearings, the prevailing regime is called elastohydrodynamic lubrication (EHL) (Hamrock et al., 2004; Stachowiak & Batchelor, 2014).

In EHL contacts:

High contact pressures lead to significant elastic deformations in the contacting bodies.

The viscosity of the lubricant is strongly pressure-dependent and can increase by orders of magnitude.

In many practical cases, surface roughness is comparable to film thickness, and this effect is particularly pronounced in mixed lubrication regimes.

Modern EHL models thus typically require the simultaneous solution of the Reynolds equation, elasticity, and energy equations, incorporating measured roughness profiles and non-Newtonian rheology (Hamrock et al., 2004). The concept of micro-EHL further extends this by explicitly accounting for the local film collapse and friction effects of individual asperities, surface defects, and textures (Ge et al., 2024; Meng et al., 2022).

Boundary Lubrication and Interface Chemistry

When the lubricant film thickness is very small compared to the surface roughness, the system operates in the boundary lubrication regime. In this regime, the primary processes occur within a few molecular layers at the interface, and volumetric fluid models become insufficient (Bhushan, 2013b; Stachowiak & Batchelor, 2014).

Current boundary lubrication research focuses on tribochemistry: how do lubricant additives and surface phases react under load and temperature to form tribofilms? For example, ZDDP and other phosphorus-containing additives decompose to form complex phosphate-based films, the composition, hardness, and adhesion of which are characterized and related to friction and wear behavior (Meng et al., 2022). Additionally, there is growing interest in triboelectric and electrochemical phenomena, particularly the effects of electric fields on nano-additives and interface reactions, which are a key research area for electric drive systems.

Smart and Adaptive Lubrication

Another recent development in lubrication science is the emergence of smart or adaptive lubricants that dynamically respond to external stimuli. Examples include:

Magnetorheological and electrorheological fluids: These fluids can adjust their apparent viscosity or flow stress in response to magnetic or electric fields.

Self-healing polymers and gels: These materials can seal micro-cracks in lubricant films or surface layers.

Micro- and nano-encapsulated additives: These release active agents when local stress or temperature exceeds certain thresholds (Meng et al., 2022; Nasser et al., 2024).

The formulation space for such lubricants is high-dimensional and complex. Machine learning and optimization methods are increasingly used to effectively explore this design space to meet multiple objectives, such as friction reduction, wear resistance, cost, and environmental compatibility (Sose et al., 2023; Zahoor et al., 2025).

Green Tribology and Sustainable Lubrication

One of the most prominent conceptual shifts in lubrication research has been the rise of the green tribology approach (Nosonovsky & Bhushan, 2012, 2013). Green tribology questions how the technical performance of tribological systems can be preserved or even improved while minimizing environmental and health impacts. Freschi et al. (2022) proposed twelve principles of green tribology, including energy efficiency, the use of non-toxic and biodegradable lubricants, material savings, recycling, and a life-cycle approach. In practice, this has led to:

The development and testing of plant-based oils, ionic liquids, and bio-derived additives as alternatives to traditional mineral oils (Rahmani et al., 2024),

Efforts to reduce friction-induced losses in renewable energy technologies like wind turbines, hydro turbines, and electric vehicles (Holmberg & Erdemir, 2017; Meng et al., 2022),

Encouraging the broader adoption of life-cycle assessments to consistently compare the environmental impacts of different lubrication strategies.

In this way, tribology is becoming increasingly integrated into broader sustainability discussions, with tribologists working more closely with environmental scientists and policymakers.

Notribology and Surface Engineering

Nanotribology has evolved from a niche topic to a central component of surface engineering. Findings about nanoscale friction and wear provide direct input to the design of coatings, thin films, and microcomponents across a wide range of technologies (Bhushan, 2013a, 2013b).

Key themes in this field include:

High-Resolution Measurements: AFM-based friction measurements, nano-hardness testing, and in-situ TEM experiments provide detailed friction, adhesion, and wear maps that are correlated with microstructural features (Malav & Tyagi, 2019; Sadeghi et al., 2024).

Nanoengineered Coatings and Two-Dimensional Materials: Diamond-like carbon (DLC) coatings, nitrided coatings, ceramic films, and two-dimensional materials like graphene and MoS2 are designed to provide combinations of low friction, high wear resistance, and chemical stability (Bhushan, 2013a; Nasser et al., 2024).

Nanoparticle Additives: The dispersion of nanoparticles such as ZnO, TiO2, MoS2, graphene, and carbon nanotubes in lubricants has been shown to reduce friction and wear in numerous laboratory configurations by acting as rolling elements, sacrificial layers, or polishing agents (Nasser et al., 2024).

Unique Nanoscale Wear Mechanisms: Nanoscale wear may involve only a few atomic layers undergoing amorphization, phase changes, or reorganization, which requires explanations beyond classical volumetric wear models (Malav & Tyagi, 2019; Sadeghi et al., 2024).

Thus, nanotribology is directly related to applications such as MEMS/NEMS devices, data storage technologies, precision positioning systems, and biomedical implants, where thin layers need to provide reliable tribological performance over extended periods.

Biotribology and Biomimetic Design

Biotribology examines the friction, wear, and lubrication phenomena in biological systems and explores how these systems can inspire engineering solutions. Biological joints, skin, eyes, and teeth are examples of tribological systems that have undergone long-term evolutionary optimization under mechanical and physiological constraints (Norris, 2008; Ghosh et al., 2017).

Joint Lubrication as a Tribological Benchmark

Human hip and knee joints are often used as benchmarks for ultra-low friction. Under proper conditions, effective friction coefficients approaching 0.001 have been reported (Ghosh et al., 2017). This remarkable performance results from the interaction of the following factors:

Cartilage with depth-dependent composition and microstructure that serves both load-bearing and lubrication functions, Synovial fluid containing complex molecular mixtures such as hyaluronic acid, lubricin, proteoglycans, and phospholipids,

Multiple lubrication mechanisms, including boundary, mixed, and hydrodynamic regimes, within the porous cartilage matrix (Norris, 2008; Ghosh et al., 2017).

Biotribological research aims to replicate these essential features in artificial joints. Proposed strategies include hydrogel and polymer coatings, advanced bearing materials, and lubricants that mimic the rheology and chemistry of synovial fluid (Ghosh et al., 2017; Li & Wang, 2023).

Biomimetic Surfaces and Their Connection with Green Tribology

There are numerous examples in nature of surface designs that are tribologically interesting: gecko footpads that enable controlled adhesion, anisotropic friction in snake skin, and superhydrophobic, self-cleaning lotus leaves and insect wings (Nosonovsky & Bhushan, 2012, 2013).

These biological templates inspire the design of surfaces with:

Directed friction for grip and motion control, Self-cleaning properties that limit friction increase due to contamination, Water-based or "bio-lubricated" interfaces through hydrogels or other hydrated coatings.

Biomimetic approaches have strong synergy with green tribology: by replicating biologically evolved solutions, it is often possible to design tribosystems that are both high-performance and less harmful to the environment.

Energy Efficiency, Sustainability, and System-Level Tribology

Tribology has significant implications for energy and resource efficiency. Global analyses indicate that realistic improvements in tribological applications could lead to energy savings ranging from 20–40% in some industries (Holmberg & Erdemir, 2017).

At the system level:

Bearings, gears, seals, and other components are evaluated not only for local contact stresses and friction but also for their impact on overall efficiency, vibration, noise, and thermal management (Holmberg & Andersson, 2012; Stachowiak & Batchelor, 2014).

Lubricant and material selections are analyzed using a life-cycle approach that encompasses manufacturing, use, maintenance, and disposal (Freschi et al., 2022; Rahmani et al., 2024).

In sectors such as wind turbines, rail systems, and electric vehicles, tribological optimization is closely linked to energy and emissions targets, leading to sector-specific guidelines (Holmberg & Erdemir, 2017; Meng et al., 2022).

Thus, tribology is increasingly recognized as a key lever in achieving sustainability goals, both at the facility and societal scale.

Digital Tribology: Digital Twins and Machine Learning

The digitalization of tribology brings together many of the themes discussed so far—advanced sensing, multiscale modeling, and machine learning. This convergence is captured by the concept of digital tribology (Sose et al., 2023; Zahoor et al., 2025).

Digital Twins of Tribosystems

A digital twin of a tribological system is a virtual representation that typically reflects the state of the physical system in near real-time. A tribological digital twin includes:

Geometric and kinematic information obtained from CAD models, Material and surface properties measured from experiments or simulations, Physics-based sub-models for friction, wear, and lubrication, Sensor data such as vibration, torque, temperature, acoustic emissions, and lubricant condition.

By continuously reconciling model predictions with sensor data, the digital twin can predict current wear conditions, forecast remaining useful life, and support decisions regarding maintenance, operating conditions, and design changes (Zahoor et al., 2025).

Predictive and Optimized Tribology Using Machine Learning

Machine learning is used in tribology to complement physics-based models by capturing complex patterns and interactions directly from data (Sose et al., 2023). In tribology, machine learning is applied in the following ways:

Regression and classification models: These are created to predict friction, wear, and temperature under varying conditions, based on inputs such as load, speed, and lubrication type (Roslan et al., 2025; Sose et al., 2023).

Surrogate models for computationally expensive numerical simulations: These surrogate models make design exploration and optimization feasible for complex systems (Ge et al., 2024).

Material, coating, and lubricant formulation selection: Machine learning models rank and select materials or formulations with predicted tribological performance (Zahoor et al., 2025).

A significant new trend is physics-informed machine learning, where physical constraints and prior knowledge are incorporated into learning algorithms. This approach improves the reliability of predictions, especially when extrapolating beyond the training data range (Zahoor et al., 2025).

Conclusions from a Mechanical Design Perspective

From a mechanical engineering perspective, the paradigms summarized above have a number of practical implications:

Tribology should be integrated early in the design process: Friction and wear considerations should be integrated into the conceptual and preliminary design stages, not merely as corrections in later stages (Bhushan, 2013a; Stachowiak & Batchelor, 2014).

Surfaces are active design elements: Surface roughness, anisotropy, and texture should be considered as design parameters to be optimized, not simply as by-products of manufacturing tolerances (Ge et al., 2024).

Material selection must include tribological criteria: Wear resistance, contact fatigue behavior, and chemical stability under working conditions should be explicitly considered alongside classical mechanical properties such as strength, stiffness, and cost (Bhushan, 2013a; Meng et al., 2022).

Lubrication systems are part of the architecture: The type of lubricant (oil, grease, water-based or bio-based), feeding method, and conditioning system selection are critical not only for component life but also for efficiency and environmental impact (Freschi et al., 2022; Rahmani et al., 2024).

Detection and data processing are design requirements: For critical tribosystems, the infrastructure for monitoring and data analysis (sensor placement, data collection, and processing) should be considered from the beginning of the design process to enable condition-based and predictive maintenance strategies (Sose et al., 2023; Zahoor et al., 2025).

Future Research Directions

The trends discussed in this chapter point to several promising areas for future research in tribology:

Standardized and curated tribological databases: Carefully curated, standardized data sets will support triboinformatics research, enable robust machine learning models, and increase reproducibility across laboratories (Sose et al., 2023; Zahoor et al., 2025).

Physics-informed and interpretable AI: Developing machine learning models that incorporate physical constraints, quantify uncertainty, and provide conceptual insights—not just numerical predictions—remains a major challenge (Zahoor et al., 2025).

Scalable superlubricity: Translating the carefully controlled nanoscale experiments on superlubricity to practical macroscopic applications will require new materials, surface architectures, and system integration strategies (Malav & Tyagi, 2019; Nasser et al., 2024).

Tribology for low-carbon technologies: As transportation and energy systems decarbonize, tribological solutions will need to be adapted to meet the specific needs of electric drive systems, renewable energy devices, and new industrial processes (Holmberg & Erdemir, 2017; Meng et al., 2022).

Advanced biotribology: A better understanding of tribological processes at the tissue and cellular level could lead to the development of more durable implants, advanced prosthetics, and new bio-inspired lubricants (Ghosh et al., 2017; Li & Wang, 2023).

Thermodynamic formulations and design standards: Continued development of energy- and entropy-based wear models may pave the way for generalized design criteria that could eventually be incorporated into engineering standards (Meng et al., 2022; Zahoor et al., 2025).

Taken together, these trends suggest that tribology will play a central role in the design of efficient, reliable, and sustainable mechanical systems, with data-driven, multiscale, and fully integrated approaches leading the way.

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VENTILATION

MUSA DEMİR[2]

Air: Air is a gaseous mixture that makes up the atmosphere and is composed mainly of roughly 78% nitrogen, 21% oxygen, 0.93% argon, and trace amounts of carbon dioxide, water vapor, and other inert gases. From a thermodynamic perspective, air is considered a fluid whose density, temperature, pressure, and moisture content are continuously changing; thus, its behavior in engineering applications can be estimated using the ideal gas laws (Çengel 2000).

The water vapor contained in the air allows it to be classified as either "dry air" or "moist air," and it is this moisture content that forms the basis for the heat and mass transfer processes carried out in HVAC systems.

Since air is the heat-carrying fluid in all conditioning systems, the required comfort conditions of a space are reached through the various thermodynamic processes that air within the AHU undergoes.

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Within this context, all the stages of conditioning take place inside the AHU, including cleaning and washing the air that is contaminated, humidifying dry air, dehumidifying moisture-laden air, heating cold air, and cooling warm air, and delivering appropriately conditioned air to the space (DOĞAN 2017).

1.1. Types of Air:

Dry Air: Air that contains no water vapor (Cengel and Boles 2002).

Moist Air (Wet Air): If enriched with water vapor, the air is referred to as moist or wet air. Since it carries a significant amount of thermal energy, the air considered in HVAC processes is always moist air (Çengel, Cimbala, and Engin 2008).

Return Air: Return air is the stale air extracted from the conditioned space and routed to the mixing chamber to be blended with a specified amount of outdoor fresh air to improve energy efficiency. Return air is an important component of HVAC systems, particularly for energy recovery.

Mixed Air: Mixed air is the system air formed in the mixing chamber by combining outdoor air and return/stale air in predetermined proportions.

Exhaust Air (Waste Air): After being used in the conditioned space, air with reduced oxygen content, increased contaminant concentration, and properties that no longer meet comfort criteria is expelled from the system as exhaust (waste) air. This air is typically discharged to the atmosphere through exhaust ducts (DEMİR and GÜNER 2023).

Stale Air: Air extracted from indoor spaces that has become polluted and depleted in oxygen due to use is defined as stale air. Depending on the system design, stale air is either fully exhausted or partially routed to the mixing chamber as return air.

Clean Air (Conditioned Air): Air that has been conditioned within the AHU through heating, cooling, humidification, dehumidification, and filtration to meet the required indoor conditions is referred to as clean or conditioned air. This air is supplied to the indoor environment through the supply ducts to ensure comfort conditions within the space (Yamankaradeniz et al. 2015).

1.2. Required Air Conditions:

The air used as the primary heat-carrying fluid in HVAC systems must meet specific physical and chemical requirements. Achieving the intended comfort, health, and hygiene conditions during the design of an HVAC installation depends on accurately defining these air properties and incorporating them into engineering calculations.

The primary attributes considered in the evaluation of air for conditioning purposes include its freshness level, cleanliness, humidity ratio, temperature, and flow velocity. These parameters not only directly influence occupants' thermal and hygienic comfort but also play a decisive role in the system's energy efficiency and overall performance.

1.2.1. Freshness of Air:

Fresh air is the oxygen-rich outdoor air. All living organisms need a minimum level of oxygen concentration to sustain life. Although the percentage of oxygen in inhaled air is about 21%, this concentration decreases to about 16.5% in exhaled air. Therefore, it can be said that exhaled air becomes oxygen-poor. Because of this fact, air supplied into indoor spaces should be mixed with outdoor air rich in oxygen.

1.2.2. Cleanliness of Air:

One of the most critical determinants of indoor air quality concerns air cleanliness. Any unwanted gases, particles, and dust suspended in the flow of air can have adverse effects on human health and comfort conditions. Therefore, depending on the quality of the air that enters the air-handling unit, appropriate filtration components must be employed to remove all forms of contaminants from the airflow.

1.2.3. Humidity of Air:

The discomfort sensation is felt when the moisture content in indoor air is excessively high. Air with a higher humidity carries more water vapor and feels heavy, which makes latent heat transfer from the human body slower. On the other hand, in places that are too dry, the loss of water from the body is greater, causing people to feel thirsty often. For comfort-conditioned spaces, it is normally advisable to keep the relative humidity level within the range of 40–60%.

1.2.4. Air Temperature:

In order to identify the air temperature that will be used in HVAC systems, both the indoor temperature and the outdoor air temperature values need to be predetermined in advance. In this regard, temperature charts were developed considering the average outdoor air data of different climate zones and the functional purpose of the conditioned spaces. These charts are used in system design and engineering calculations (Çakar et al.).

Table 1. Recommended Temperature and Relative Humidity Levels (Carrier,.1960).

Intended Use of Space	Summer – Luxury Temperature (°C)	Summer – Luxury Relative Humidity (%)	Summer – Normal Temperature (°C)	Summer – Normal Relative Humidity (%)	Winter – Temperature (°C)	Winter – Relative Humidity (%)
Residence, hotel, office, hospital, school	23–24	50–45	25–26	50–45	23–24	35–30
Shop, bank, barber, supermarket	24–26	50–45	26–27	50–45	22–23	35–30
Conferencehall, restaurant	24-26	55–50	26–27	60–50	22–23	40–35
Factory, machineryand assembly workshop	25–27	55–45	26–27	69–50	20–22	35–30

Table 2. CIBSE A ENVIRONMENTAL DESIGN (Lush, Butcher, and Appleby 1999).

Building / Room Type	Winter Temp (°C)	Activity (met)	Clothing (clo)	Summer Temp (°C)	Activity	Clothing	Filtration	Illuminance (lux)	Noise Rating (NR)
Airport terminals – baggage reclaim	12–19	1.8	—	21–25[1]	1.8	0.65	8[2], F6–F7	200	45
Airport terminals – check-in areas	18–20	1.4	—	21–23	1.4	0.65	8[2], F6–F7	500[4]	45
Airport terminals – concourse (no seats)	12–19	1.8	—	21–25	1.8	0.65	8[2], F6–F7	200	45
Airport terminals – customs area	18–20	1.4	—	21–23[1]	1.4	0.65	8[2], F6–F7	500	45
Airport terminals – departure lounge	19–21	1.3	—	22–24	1.3	0.65	8[2], F6–F7	200	40
Banks – counters	19–21	1.4	—	21–23	1.4	0.65	8[2], F6–F7	500	35–40
Banks – public areas	19–21	1.4	—	21–23	1.4	0.65	8[2], F5–F7	300	35–45
Bars / lounges	20–22	1.3	—	22–24	1.3	0.65	8[2], F5–F7	100–200	30–40
Churches	19–21	1.3	—	22–24	1.3	0.65	8[2], G4–F6	100–200	25–30
Computer rooms	19–21	1.4	—	21–23	1.4	0.65	8[2], F7–F9	300	35–45
Conference / board rooms	22–23	1.1	—	23–25	1.1	0.65	8[2], F6–F7	300/500[7]	25–30

1.2.5. Air Velocity:

Air velocity plays a critical role in maintaining indoor thermal comfort. When the airflow is excessively low, a stagnant air layer forms around the body, hindering latent heat transfer from the skin to the environment and causing a sensation of oppressive warmth. Conversely, excessively high air velocity creates a draft effect, particularly in seating and resting areas, leading to thermal discomfort. Therefore, indoor air movement should be neither completely stagnant nor uncomfortably fast; instead, it must remain controlled and within acceptable comfort limits (Handbook 1997).

Based on experimental studies and field observations, it has been shown through numerous studies that under acceptable conditions for thermal comfort, indoor air velocities should be approximately 0.2–0.3 m/s at normal room temperatures. This level of air velocity provides thermal comfort for the occupant and protects against draughts, which is essential for providing a healthy air movement pattern indoors. (Doğan 2002).

2.Ventilation and Types of Ventilation

An air-handling unit is an integrated system consisting of different functional units assembled in a prescribed arrangement. Each unit in the AHU represents a different stage of the air-conditioning process. Commonly, an AHU also includes ventilation ducts and duct connection accessories. Ventilation ducts along with their fittings are jointly known as the ventilation system.

The dictionary defines ventilation as the renewal of air in enclosed spaces by various methods and apparatuses. Clean outdoor air is introduced inside, polluted air is exhausted, and directional airflow is created to regulate indoor air movement. The purpose of ventilation is, therefore, to preserve and improve indoor air quality by diluting and removing contaminants generated within the space.

Thus, maintaining the health, comfort, and quality of indoor living conditions of occupants sustainably. Ventilation systems can be classified into three basic categories.

1. Natural Ventilation
2. Hybrid (Mixed-Mode) Ventilation
3. Mechanical Ventilation

2.1. Natural Ventilation

Natural ventilation is a ventilation method that relies entirely on passive physical processes, in which outdoor air enters the indoor space and polluted indoor air is expelled without the use of any mechanical system. In this system, air movement occurs through natural driving forces such as wind pressure and the stack effect generated by temperature differences. The air exchange achieved by opening doors and windows in daily life represents the most basic form of natural ventilation. Since this method requires no energy consumption, it provides a simple, economical, and environmentally friendly ventilation solution; however, its performance depends heavily on outdoor weather conditions (Çakmanus 2005).

2.2. Hybrid (Mixed-Mode) Ventilation

Natural–mechanical (hybrid) ventilation is defined as a combined system in which natural ventilation and mechanical ventilation are used together. In this approach, part of the airflow is driven by natural physical processes, while mechanical devices are employed when necessary to enhance system performance. To illustrate with a simple example: in a residence, ceiling-mounted exhaust fans are used to remove polluted air from bathroom areas, directing the air toward a ventilation shaft. A wind-driven cowl (air-direction device) mounted at the top of the shaft creates positive or negative pressure differences under wind action, thereby supporting the airflow. Thus, the mechanical extraction provided by the exhaust fan and the wind-induced natural airflow operate together, resulting in more effective ventilation.

2.2.1.Positive Pressure: Positive pressure refers to a condition in which the air pressure inside a space is higher than that of the outdoor environment. In this case, air flows from the indoor space toward the outside; the indoor air escapes outward, and outdoor air cannot infiltrate.

2.2.2.Negative Pressure: Negative pressure denotes a condition in which the air pressure inside a space is lower than the pressure of the outdoor environment. In this condition, airflow occurs from the outside toward the inside; outdoor air enters the space, and contaminated air is prevented from leaking into adjacent areas. Vacuum pressure essentially corresponds to negative pressure, although differences exist in how the terms are used.

Negative pressure refers to a pressure within a space that is lower than atmospheric pressure. This difference may be small or large, as in the slight negative pressure generated by a bathroom exhaust fan or the suction pressure within a ventilation shaft.

Vacuum pressure encompasses all pressures below atmospheric pressure; however, in common usage, the term “vacuum” typically refers to a stronger or deeper level of negative pressure.

Table 3. Example illustrating the difference between negative pressure and vacuum pressure

Term	Meaning	Pressure Difference Level
Negative Pressure	Pressure lower than atmospheric pressure	May involve small differences (e.g., –5 Pa, –20 Pa)
Vacuum Pressure	All pressures below atmospheric pressure	Generally refers to larger differences (e.g., –50 kPa, –90 kPa)

In conclusion, every vacuum is a form of negative pressure, but not every negative pressure is considered a vacuum (because the pressure difference may be very small).

2.3. Mechanical Ventilation:

Mechanical ventilation is a ventilation method in which air in enclosed spaces is moved in a controlled manner using mechanical equipment. In such systems, airflow is generated through supply (blowing) or exhaust (suction) principles using exhaust fans, ventilator fans, or similar mechanical drive components. The use of electrical energy to drive air movement is the fundamental distinguishing feature of mechanical ventilation.

Mechanical ventilation systems include not only simple fan applications but also more complex air-conditioning and air-handling components. In this context, components such as:

- Air-handling units (AHUs),
- Heat recovery units (HRUs),
- Fan-coil units (FCUs),
- Cooling towers

are all considered part of mechanical ventilation systems. These devices regulate the airflow rate, temperature, humidity, and cleanliness of the air supplied to or extracted from the space to meet required conditions.

Mechanical ventilation systems are preferred in modern buildings to maintain indoor air quality, ensure thermal comfort, and achieve energy-efficient operating conditions (Awbi 2008).

3. Classification of Ventilation Ducts:

Duct systems used in ventilation installations are classified according to criteria such as air volume flow rate, air velocity, and total pressure loss. This classification is of great importance for evaluating system performance, selecting appropriate materials, ensuring energy efficiency, and meeting safety requirements (Nehme).

Ventilation Duct Types:

- Ducts Classified by Airflow Velocity
- Ducts Classified by Pressure Class (mmWC – mmSS)
- Ducts Classified by Material
- Ducts Classified by Cross-Section Shape
- Ducts Classified by Functional Use
- Ducts Classified by Construction Type

3.1. Classification of Ducts by Airflow Velocity

Ventilation ducts are examined in two main categories based on the airflow velocity within them: low-velocity ducts and high-velocity ducts.

3.1.1. Low-Velocity Ducts

Low-velocity duct systems cover applications in which the air velocity is up to 10 m/s.

These types of ducts are commonly used especially in: Comfort-oriented HVAC systems, Office, residential, and commercial building applications. In Türkiye and in projects based on international standards, typical duct air velocities used in comfort applications generally range between 7–9 m/s. Low air velocity provides advantages in reducing noise levels and minimizing energy losses.

3.1.2. High-Velocity Ducts

Duct applications in which the air velocity exceeds 10 m/s fall into the high-velocity duct category (Güney, Kaygusuz, and Reviews 2010). These ducts are primarily used in:

• Fire protection system connections,

• Smoke exhaust systems,

• Stairwell pressurization applications,

• Industrial ventilation and process exhaust systems.

In industrial environments and in safety-related systems activated during fire conditions, air velocities may reach up to 20 m/s.

3.2. Classification of Ducts by Pressure Class (Pressure Level)

The second major classification method for ventilation ducts is based on the total pressure loss within the system. The unit of pressure used is mmWC (millimeters of water column), which represents the pressure exerted at the base of a 1 mm column of water at +4 °C.

The classification widely accepted in industry practice and technical literature is as follows:

Systems up to 100 mmWC → Low-Pressure Ducts; commonly used in comfort ventilation and standard distribution lines.

Systems up to 175 mmWC → Medium-Pressure Ducts; preferred in heat recovery units, fan-coil unit connections, and medium-scale distribution networks.

Systems up to 300 mmWC → High-Pressure Ducts; used in industrial applications, long-range distribution, smoke exhaust systems, and fire-safety scenarios.

This classification directly influences duct material strength requirements, flange system selection, and the specification of air leakage classes (Committee 1960).

3.3. Ducts Classified by Material

3.3.1. Galvanized Steel Ducts:

They are used in supply and return sections of heat recovery units, air-handling units, WC and bathroom ventilation systems, offices, shopping malls, and non-sterile areas of hospitals, as well as in general-purpose ventilation applications (Cameron 1960).

Figure 1. Duct constructed from galvanized steel sheet (Karsac 2025).

3.3.2. Black Steel Ventilation Ducts:

Black steel ventilation ducts are preferred in specific applications due to their high temperature resistance and superior structural strength against fire conditions. They are used particularly in systems involving high-temperature airflow and in areas where fire safety is of critical importance.

This duct type is commonly used in applications such as:

- Smoke exhaust lines,
- Fire-scenario ventilation systems,
- High-temperature kitchen hood exhausts,
- Hot gas or steam transport lines in industrial processes.

Since black steel ducts can withstand higher temperatures and fire loads compared to galvanized steel ducts, they provide a reliable solution in applications mandated by fire safety regulations.

Figure 2. Ventilation duct constructed from black steel sheet (Alafcohvac 2025).

3.3.3. Aluminum Ducts

They are lightweight, corrosion-resistant ducts commonly used in clean rooms and laboratory environments.

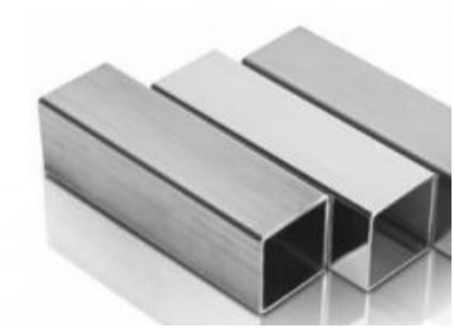

Figure 3. Aluminum duct illustration (Alminyum 2025).

3.3.4. Stainless Steel Ventilation Ducts

Ventilation ducts manufactured from stainless steel are critically important in specific applications due to their high hygiene requirements, chemical resistance, and ease of cleaning. Their superior corrosion resistance and smooth surface structure provide advantages in terms of mechanical durability and maintaining hygienic conditions. For these reasons, stainless steel ducts are preferred particularly in environments requiring high hygiene and chemical resistance such as operating rooms, intensive care units, sterile zones, food production facilities, pharmaceutical and chemical industries, commercial and industrial kitchens, and laboratory areas (Güney 2010).

Figure 4. An illustration of stainless steel ventilation ducts (DuctStore 2025).

3.3.5. Flexible Ventilation Ducts (Flex Ducts):

They exist in two types: insulated and uninsulated. Uninsulated flexible ducts are used in areas where heat recovery is not required, such as toilet exhaust applications.

Figure 5. Uninsulated flexible ventilation duct (a-tec 2025).

When heat transfer control is important, insulated flexible ventilation ducts are preferred.

Figure 6. Insulated flexible ventilation duct (a-tec 2025).

3.3.6. Fabric (Textile) Air Ducts

They provide uniform air distribution in large-volume spaces such as sports halls, warehouses, and industrial facilities. They are lightweight and easy to install. Fabric ventilation ducts can be used only in positive-pressure supply lines; their use in negative-pressure return or exhaust lines is technically unsuitable. They may undergo physical deformation such as shrinking, collapsing, tearing, or obstruction of airflow.

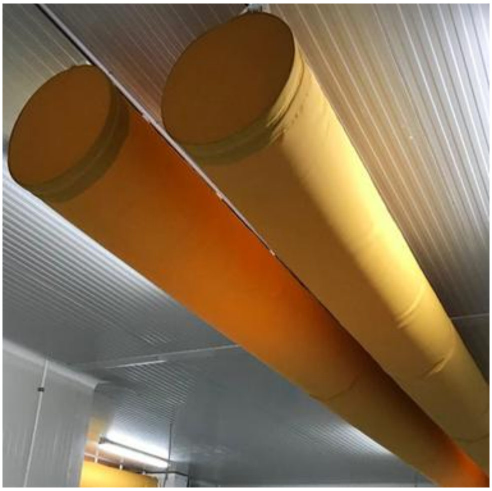

Figure 7. Fabric ventilation ducts (Mühendislik 2025).

3.3.7. Pre-Insulated Panel Ducts (PIR / PUR)

They are manufactured in the form of prefabricated sandwich panels.

Figure 8. Pre-insulated air duct panel / PIR sandwich panel (GFI 2025).

3.4. Ducts Classified by Cross-Section Shape:

3.4.1. Rectangular Ducts: They are the most commonly used duct type in buildings. They provide space efficiency in ceiling voids and shaft areas.

Figure 9. Rectangular duct illustration (Teknik 2025).

3.4.2. Circular Ducts: They are more efficient aerodynamically. They provide lower friction losses and reduced air leakage. They are preferred in industrial facilities and large-volume buildings.

Figure 10. Circular duct illustration (Meridyen 2009).

3.4.3. Oval Ducts: They combine the characteristics of both rectangular and circular ducts. They offer high airflow capacity with low pressure drop.

Figure 11. Oval duct illustration (SYSTEMS 1995).

3.5. Ducts Classified by Functional Use

3.5.1. Fresh Air Ducts: They deliver clean outdoor air into the indoor environment.

3.5.2. Exhaust Ducts: They remove contaminated air from the space to the outside.

3.5.3.Return Air Ducts: They transport indoor air back to the air-handling unit (AHU).

3.5.4.Mixed Air Ducts: They are used in the section where outdoor air and return air are mixed in specified proportions.

3.5.5.Smoke Exhaust Ducts: They are designed to exhaust hot smoke from the building during a fire.

3.5.6. Stairwell Pressurization Ducts: They maintain escape stairwells under positive pressure during fire conditions.

3.5.7. Laboratory Exhaust and Chemical Process Ducts:

They require special materials for conveying acids, solvents, or chemical gases.

3.6. Ducts Classified by Construction Type:

3.6.1. Flanged Ducts:

Used in large cross-sections and provide robust mechanical connections.

3.6.2. Non-Flanged (Ductboard/Connector) System Ducts: They offer lighter and more economical installation.

3.6.3. Modular Panel Ducts: They are formed by assembling factory-manufactured panels on site.

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VENTILATION SYSTEM EQUIPMENT

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MUSA DEMİR[4]

Grilles

Single-Row Blade Grille:

Used for extracting return air in ventilation and air-conditioning systems. These grilles are suitable for both horizontal and vertical applications, and their adjustable blades allow the direction of the return air to be controlled. In this way, the airflow can be drawn in a regulated manner. They are primarily preferred for air extraction purposes.

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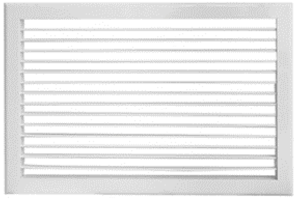
Figure 1. *View of the Single-Row Blade Grille*



Kaynak: (TROX 1951)

1.2. Double-Row Blade Grille:

It is used for distributing supply air into the indoor space in ventilation and air-conditioning systems. The double-row blade structure allows air to be discharged in the desired direction and quantity. It is used for supply-air delivery. Both grille types are widely preferred in large spaces such as shelters, storage areas, and factories, especially in locations without suspended ceilings. However, they are less favored by architects due to aesthetic concerns. In both grille types, an optional damper can be installed to allow for adjustment. Dampers enable precise control of airflow and contribute to maintaining air balance within the system.

Figure 2. *View of the Double-Row Blade Grille (KESKLİMA 1987)*

It has been determined that when comfort conditions cannot be achieved in an indoor space, approximately 70% of the issues are associated with incorrect grille selection. Therefore, in any problem situation, the grille selection should be the first element to be reviewed. For example, improper air volume selection, insufficient grille perforation, or an inadequate ΔT difference between the room temperature and the supply-air temperature are common factors that lead to poor air distribution.

What Is Balancing (Regulation) Adjustment?

Balancing adjustment, performed in radiator heating systems to ensure that all radiators connected to the heating line warm up uniformly, is achieved by adjusting the radiator valves. This procedure ensures that each point of the radiator reaches the same temperature. Similarly, in ventilation systems, balancing adjustments are made on grilles to achieve an even distribution of airflow and maintain air balance throughout the space.

1.3. Circular-Shaped Grille

Since the duct is circular, the grille must also be compatible with the duct. To prevent leakage and air loss, it should be explicitly stated that the ventilation duct is circular when ordering circular-shaped grilles. In addition, the “diameter/2” rule must be observed. For example, if the duct diameter is 60 cm, the side length of the grille should not exceed 30 cm. Otherwise, the grille will not fit properly onto the duct, leading to air leakage. Compared to circular-shaped grilles, single- or double-row grilles can be mounted directly onto the duct much more conveniently, which increases system efficiency.

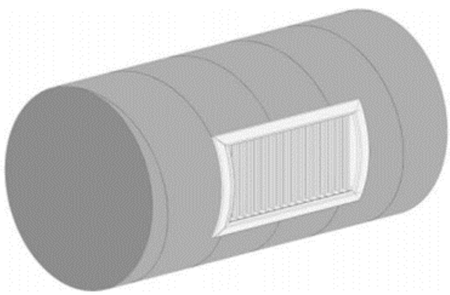


Figure 3. *Circular-Shaped Grille (ÇEPİK 1995)*

1.4. Door Grille:

It enables air transfer by creating a pressure difference and is used to regulate airflow between spaces with different pressure levels. In typical ventilation applications, the main room is maintained at a positive pressure while restrooms are kept at a negative pressure, ensuring that air flows from the occupied space toward the restroom. In this way, unwanted odors and contaminants are prevented from spreading into the main area.

Figure 4. *Door Grille View (Artedoor 2024)*

1.5. Linear Grille:

It is generally preferred in areas where an architectural recess or alcove is created. A common application is the installation of a plenum box in front of Variable Refrigerant Volume (VRV) or fan-coil units in hotel rooms, followed by the placement of a linear grille. VRV is a type of air-conditioning system capable of providing heating and cooling by supplying multiple indoor units from a single outdoor unit. In this way, a controlled air stream is delivered parallel to the ceiling. The projections known as “anıl,” which belong to the same family as single- or double-row grilles, are used in special applications. They are shown with an arrow in Figure 5.

Figure 5. *Linear Grille View (İklimlendirme 1999)*

2. Anemostats

2.1. Square Anemostat:

It is generally preferred in applications requiring higher air volumes. It can be manufactured in square or rectangular form. It is most commonly used together with a rectangular plenum box.

Figure 6. *Square Anemostat (TROX 1951)*

2.2. Circular Anemostat:

It is widely used particularly in cafés, areas without suspended ceilings, and circular ducts. Compared to the square anemostat type, it provides lower internal resistance and generates less noise.

Figure 7. *Circular Anemostat (KESKLİMA 1987)*

2.3. Marine-Type Anemostat:

Structurally, it resembles circular anemostats. Automatic exhaust marine-type anemostats are suitable for installation in multi-story buildings, business centers, hotels, schools, and other facilities equipped with a centralized exhaust system.

Figure 8. *Anemostats Preferred in Multi-Story Buildings (AFS 1991)*

It is also a highly economical solution for small spaces where low air volume is required, as this type of anemostat provides easy installation and efficient ventilation.

Figure 9. *Easily Installed Anemostat for Low Airflow Rates (AFS 1991)*

Grilles and anemostats serve the same general function; however, there are a few notable differences between them. A grille directs the airflow straight forward in a vertical manner, whereas an anemostat can distribute the supply air into 2, 3, or 4 directions depending on the requirement. Grilles have a simpler appearance, while anemostats offer a more decorative look.

Ölçüler – Size E (mm) x B (mm)	Debi – Flow Rate V (m3/h)	Atış Mesafesi – Throw L (m) VL=0,25 m/s	Basınç Kaybı - Pressure Loss ΔP (Pa)	Ses Güç Seviyesi - Sound Power Level S (dB(A))
150 x 150	120	1,0	9	<20
	160	1,2	15	<20
	200	1,5	23	25
	250	2,0	33	29
	280	2,2	43	32
225 x 225	280	1,5	9	<20
	370	2,0	15	25
	460	2,5	23	30
	550	2,7	33	34
	640	3,0	43	37
300 x 300	490	2,0	9	<20
	650	2,5	15	28
	810	3,0	23	32
	970	3,5	33	37
	1130	4,5	43	40
375 x 375	760	3,5	9	<20
	1010	4,5	15	30
	1270	5,5	23	35
	1520	6,5	33	39
	1770	7,5	43	42
450 x 450	1100	2,5	9	26
	1460	3,5	15	32
	1820	4,5	23	37
	2190	5,5	33	40
	2550	6,5	43	44
525 x 525	1490	3,0	9	30
	1980	4,0	15	35
	2480	5,0	23	40
	2980	6,5	33	45
	3470	7,5	43	45
600 x 600	1950	3,5	9	30
	2590	4,5	15	35
	3240	5,5	23	40
	3890	6,5	33	45
	4540	7,0	43	45

Ölçüler – Size E (mm) x B (mm)	Debi – Flow Rate V (m3/h)	Atış Mesafesi – Throw L (m) VL=0,25 m/s	Basınç Kaybı - Pressure Loss ΔP (Pa)	Ses Güç Seviyesi - Sound Power Level S (dB(A))
150 x 150	120	1,0	9	<20
	160	1,1	15	<20
	200	1,5	23	20
	250	2,0	33	24
	280	2,2	43	28
225 x 225	280	1,5	9	<20
	370	2,0	15	20
	460	2,5	23	25
	550	2,7	33	29
	640	3,0	43	32
300 x 300	490	2,0	9	<20
	650	2,5	15	23
	810	3,0	23	28
	970	3,5	33	32
	1130	4,5	43	35
375 x 375	760	2,5	9	<20
	1010	3,0	15	25
	1270	4,0	23	30
	1520	5,0	33	34
	1770	5,5	43	37
450 x 450	1100	2,5	9	21
	1460	3,5	15	27
	1820	4,5	23	32
	2190	5,5	33	35
	2550	6,5	43	39
525 x 525	1490	3,0	9	25
	1980	4,0	15	30
	2480	5,0	23	35
	2980	6,0	33	40
	3470	7,0	43	40
600 x 600	1950	3,0	9	25
	2590	4,0	15	30
	3240	5,0	23	35
	3890	6,0	33	40
	4540	7,0	43	40

Ölçüler – Size E (mm) x B (mm)	Debi – Flow Rate V (m3/h)	Atış Mesafesi – Throw L (m) VL=0,25 m/s	Basınç Kaybı - Pressure Loss ΔP (Pa)	Ses Güç Seviyesi - Sound Power Level S (dB(A))
150 x 150	120	1,0	9	<20
	160	1,1	15	<20
	200	1,5	23	<20
	250	1,7	33	<20
	280	2,0	43	21
225 x 225	280	1,0	9	<20
	370	1,5	15	<20
	460	2,0	23	<20
	550	2,1	33	23
	640	2,2	43	27
300 x 300	490	1,5	9	<20
	650	2,0	15	20
	810	2,2	23	25
	970	2,5	33	29
	1130	3,0	43	32
375 x 375	760	2,0	9	<20
	1010	2,2	15	24
	1270	2,5	23	29
	1520	3,5	33	33
	1770	4,0	43	37
450 x 450	1100	2,0	9	22
	1460	2,5	15	28
	1820	3,5	23	33
	2190	4,0	33	36
	2550	4,5	43	40
525 x 525	1490	2,5	9	25
	1980	3,0	15	30
	2480	4,0	23	35
	2980	4,5	33	40
	3470	5,0	43	45
600 x 600	1950	2,5	9	30
	2590	3,5	15	35
	3240	4,5	23	40
	3890	5,0	33	45

Figure 10. *Appearance of Grille Information Catalogs*

As shown in Figure 10, selections can be made directly from the catalogs. In addition, various ventilation sizing software tools are also available. For example, when the 30 × 30 cm square anemostat shown on the far right is selected, the catalog indicates a maximum airflow rate of 1130 m³/h and a minimum airflow rate of 490 m³/h. The catalogs also provide technical data such as pressure loss (in

Pascals) and sound level (in decibels) corresponding to these airflow values. These data are arranged in columns within the catalog, listed vertically from top to bottom. Typically, if there are five different values within a row, selecting the middle value is considered a reasonable and commonly preferred engineering practice.

3. Diffusers

3.1. Slot Diffuser: It is widely used in offices, particularly in front of windows. Slot diffusers are available in 1-, 2-, 3-, or 4-slot types, and the number of slots can be increased depending on the required airflow rate. They allow both vertical and horizontal air distribution. A damper option is also available.

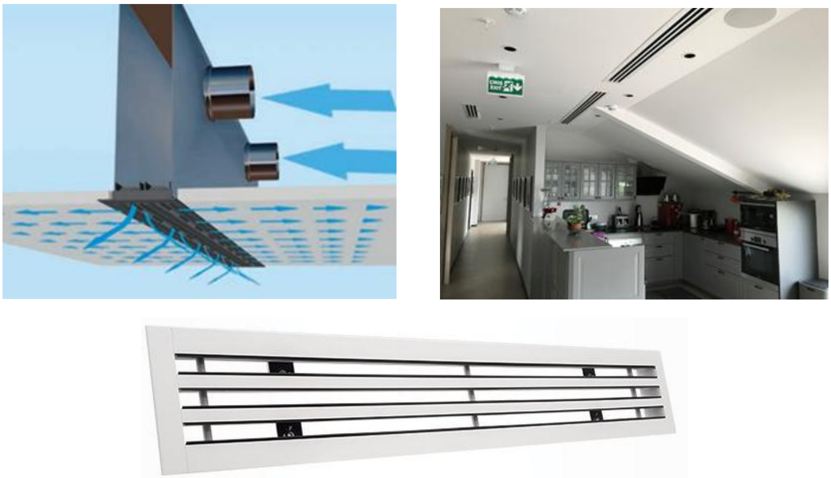


Figure 11. *Slot Diffuser (Systemair 1975)*

A damper option is available. A visual representation is provided in Figure 12.

Figure 12. *Diffuser with Damper (Systemair 1975)*

3.2. High-Ceiling Diffuser:

This type of diffuser is commonly used when the suspended ceiling height is 4 meters or higher. Warm air tends to rise due to its lower density (heated air rises), making it difficult to bring the air down to the occupied zone; therefore, the diffuser types used in such spaces are more specialized. Selection is made based on the airflow rate per diffuser and the temperature difference between the supply air and the room air. Cold air, having a higher density, naturally descends and provides directional air distribution.

Figure 13. *High-Ceiling Diffuser (TROX 1951)*

For high-ceiling diffusers, when air needs to be directed downward from heights of 4 or 5 meters, motorized systems must be used. Selections can be made according to the required airflow rates, and appropriate models can be chosen based on these values.

Figure 14. *Motorized High-Ceiling Diffusers (TROX 1951)*

4. Jet nozzles

Jet nozzles are widely used in areas such as food courts and cinema sections of shopping malls. These nozzles typically have an air-throwing capacity ranging from 5 meters to 30 meters. Due to their special design, it is recommended that their selection be carried out using dedicated sizing software.

Figure 15. *Jet Nozzles and Their Appearance in a Shopping Mall (KESKLİMA 1987)*

5. Laminar flow unit

It is used in operating rooms to provide a uniform downward supply of air and ensure a homogeneous airflow distribution from above.

Figure 16. *Laminar Flow Unit (UNTES 1968)*

6. Fiber-Trap Grilles and Exhaust Units

In operating rooms, grilles designed without sharp corners are preferred to prevent the formation of microbes and bacteria. Fiber-trap grilles are installed at duct transition points and serve to capture particulate matter. By design, these grilles are configured to perform air extraction with approximately 66% of the airflow drawn from the lower section and 33% from the upper section.

Figure 17. *Fiber-Trap Grille Used in Operating Rooms (UNTES 1968)*

7. Fans and Exhaust Units

7.1. Wall Type

Wall-mounted fans are highly compact units designed to provide air circulation within the space in which they are installed. These fans are generally preferred for ventilation and cooling purposes. They enable significant airflow even in narrow and confined areas, thereby contributing to the removal of contaminated air from the environment. Wall-type fans with multiple speed settings offer flexible operation thanks to their various functional features. Their use in workshops, offices, and industrial facilities provides both energy efficiency and practical functionality.

Figure 18. *Wall-Type Fan (ERFGRUP 1995)*

7.2. Ceiling-Type Exhaust Fan: It is commonly used in bathrooms and restrooms.

Figure 19. *Ceiling-Type Exhaust Fan (KESKLİMA 1987)*

7.3. Duct-Type Fan: It can be used both as an exhaust fan and as a ventilator.

Figure 20. *Duct-Type Fan (AFS 1991)*

7.4. Cabinet-Type Fan: This type is used for high airflow rates and is typically installed outdoors, such as on rooftops.

Figure 21. *Cabinet-Type Fan (Systemair 1975)*

7.5. Axial Fan: It is typically used in the extraction of smoke exhaust discharged by jet fans and is preferred when airflow rates reach between 30,000 m^3/h and 250,000 m^3/h.

Figure 22. *Axial Fan (Systemair 1975)*

7.6. Radial Jet Fan: It is typically used in parking garages where there is a height limitation, particularly when the ceiling height is low, such as around 30 cm of available clearance.

Figure 23. *Radial Jet Fan (AFS 1991)*

7.7. Axial Jet Fan: It is generally used in parking garages with greater ceiling height, typically where 55–60 cm or more of vertical clearance is available.

Figure 24. *Axial Jet Fan (AFS 1991)*

7.8. Shelter Ventilator: It is used for low airflow rates. There is also a shelter air-handling unit, which is designed for high airflow capacities.

Figure 25. *Shelter Ventilator (AFS 1991)*

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