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Methods of Heat Transfer Enhancement for Metals Heat Treatment Applications: A Review

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Abstract

Heat treatment is an important part of materials and metallurgical engineering. It allows the microstructure and mechanical properties to be enhanced by means of regulated thermal cycles. In Nigeria, this process is an essential one for industries such as the automotive industry, oil & gas, and construction industries. It is however, often limited by out dated equipment, insufficient quenching management and low energy efficiency. This article shows the importance of heat transfer in the metallurgical process of heat-treatment and examines the different enhancement methods to boost reliability and efficiency. The enhancement techniques which include mechanical agitation, jet impingement, nanofluids, surface modifications, ultrasonic agitation, and combined methods are examined. A comparative analysis is presented, with a focus on relevance to Nigeria's iron and steel industry. The discussions show that cheaper retrofits, like mechanical agitation and surface modifications provide the fastest return on investment; these are already being utilized in the industry. By contrast, high-capital, specialized techniques such as ultrasonic-assisted quenching, or more innovative options such as nanofluids, are more useful for specific applications where improved process control or unique thermal characteristics create the need for the added costs and complexity. Implementing these techniques will lead to a reduction in waste and improvement in energy efficiency, which will ultimately result in making our nation's metallurgical industry more competitive on a global scale.

Keywords: *Heat treatment; heat transfer; quenching; Iron and steel industry; Metal*

1. Introduction

Heat treatment is a core process in materials and metallurgical engineering. It involves controlled heating and cooling of a material to modify its microstructure and enhance its mechanical properties, without changing its shape. The primary objective of heat treatment is to modify the microstructure to achieve the optimal combination of properties for a particular application [1]. By carefully controlled thermal cycles of heating and cooling, techniques such as annealing, tempering, and quenching are utilized to modify the material's microstructure, thereby modifying its characteristics, including hardness, strength, ductility, and toughness amongst others [2, 3].

In Nigeria, heat treatment is essential in the automotive, construction, agricultural, and oil & gas industries, especially for processing steel and aluminium alloys utilized in local fabrication and maintenance sectors. Nonetheless, extensive dependence on obsolete thermal systems and inadequate management of heat transfer processes frequently results in variable product quality, energy inefficiency, and higher production expenses. These challenges frequently obstruct the competitiveness of locally produced Nigerian tools in both domestic and global markets.

Nigeria's iron and steel industry, which includes Ajaokuta Steel Company, Delta Steel Complex, rolling mills, and local foundries, continues to suffer from irregular quenching practices, energy inefficiency, amongst other losses. These gaps directly lead to inconsistencies with production, and increased expenses. The utilisation of heat-transfer enhancement techniques is therefore not just a matter of scientific advancement but it also has the potential to boost industrial competitiveness while encouraging local production.

The effectiveness of any heat treatment method is primarily determined by the speed and consistency of heat transfer. Ineffective heat transfer between metal parts and their surroundings can lead to major issues. For example, slow cooling during quenching hinders the development of martensite in steels, whereas uneven cooling may create significant thermal gradients, leading to part deformation, residual stresses, and eventual cracking [3, 4]. It is therefore crucial to regulate the heat transfer rate in order to manufacture high quality and durable metallic products.

As a result of these difficulties, there are currently a lot of ongoing research aimed at improving, and enhancing the heat transfer mechanisms [5]. These techniques are meant to enhance the heat transfer at the material's surface, leading to quicker and more consistent heating and cooling processes. Embracing these innovations in Nigeria may enhance energy efficiency, improve material performance, and propel the country towards achieving industrial self-sufficiency.

This review article offers a summary of the different methods used to improve heat transfer in the treatment of metals. It examines the basic principles that govern heat transfer and elaborates on the main passive and active enhancement methods relevant to advanced metal heat treatment. All the while, providing a comparative evaluation of their efficiency and uses, in view of practical implementation in Nigeria's metallurgical industry. The main method of heat transfer in heat treatment processes is through convection, especially during the quenching stage. As a result, the heat transfer enhancement methods examined in this paper will focus solely on those applicable to metal heat treatment, mainly concerning convection. Convection is essential in heat treatment, for heating components in a furnace (gas convection) and for cooling them in a quenching medium (liquid convection).

Several strategies to be examined will encompass the application of additives and nanofluids, active methods such as ultrasonic agitation and electromagnetic fields, passive approaches like improving the geometry of the heat treatment material, and surface microstructure modification to induce nucleate boiling [6]. Additionally, as modern techniques become more and more common, the metal heat treatment industry appears to be progressing worldwide. Process parameters are being improved more and more through the use of smart systems which combine data analysis, predictive controls, and real-time heat monitoring. These systems can yet be improved upon using heat transfer enhancement techniques to encourage more intelligent, flexible, and sustainable industrial operations.

2. Fundamentals of Heat Transfer in Heat Treatment

An understanding of primary heat transfer modes is important to appreciate why enhancement techniques operate. Heat transfer during the thermal cycling of a metallic component is a difficult process that is governed by conduction, convection along with radiation. Their relative importance changes with the specific treatment stage.

2.1. Modes of Heat Transfer

Heat transfer in the metallurgical industry involves three major modes, namely; conduction, convection, and radiation.

- **Conduction:** Conduction which is the primary mode of heat transfer in the solid metal part, is the transfer of heat through a material without utilising the motion of its particles. It is defined by Fourier's Law, which states that the rate of heat transfer (q) through a material is directly proportional to the area perpendicular to the direction of heat flow, and the temperature gradient.

$$q = \frac{-kAdT}{dx} \tag{1}$$

Where A represents the cross-sectional area (in m^2), k the thermal conductivity of the metal (in $W/m^2 \cdot K$) and dT/dx is the temperature gradient (in K/m). The thermal conductivity of the material determines how heat is distributed from the surface of the component to its core.

- **Convection:** This mode of heat transfer occurs when heat is transmitted between the surface of a material and a surrounding fluid and is facilitated by the flow of fluid particles. It occurs when heat is transferred to the liquid in a quenching bath or from the hot gases in a furnace. Newton's Law of Cooling, as illustrated below, describes it:

$$Q = hA\left(Ts - T\infty\right) \tag{2}$$

In this equation, Q represents the total rate of heat transfer (W), A is the surface area of the component, Ts is the surface temperature, $T\infty$ is the free stream or ambient temperature, and h, which is not a material feature, represents the heat transfer coefficient ($W/m^2 \cdot K$) and depends on the fluid's characteristics and the flow conditions. Increasing this coefficient is the goal of the majority of heat transfer enhancement approaches.

- **Radiation:** This describes the transfer of heat energy through electromagnetic waves. It is quite significant at the high operating temperatures that occur in heating furnaces. The Stefan-Boltzmann Law shows the net rate of radiative heat transfer between a surface and its surroundings. Due to the fourth-power dependence on absolute temperature (T^4), radiation is the most common mode of heat transfer in many high-temperature applications:

$$Q = \epsilon\sigma A\backslash(Ts\,4\text{ -}Tsurr\,4\ \backslash) \tag{3}$$

Where, ϵ is the emissivity of the surface of the material, and σ is the Stefan-Boltzmann constant ($5.67\times10-8W/m^2 \cdot K^4$).

2.2. Key Parameters

Some dimensionless parameters are used to compare various heat transfer conditions:
approaches.

- **Biot Number (Bi):** The Biot number compares the internal resistance of a body to conduction with the external resistance to convection at the surface. It is shown as:

$$Bi = \frac{Internal\,Conductive\,Resistance}{External\,Convective\,Resistance} = \frac{hL\mathrm{c}}{k\,\mathrm{solid}} \quad (4)$$

In the expression, K_{solid} is the thermal conductivity of the metal part and L_c is its characteristic length. If Bi<0.1, it means that the internal temperature gradients are negligible. If Bi>0.1, however, then high temperature gradients are occurring in the part, which might result in distortion and thermal stresses [7].

- **Nusselt Number (Nu):** The Nusselt number is a comparison between the rate of heat transfer from a surface due to fluid motion and the rate of heat transfer assuming only conduction occurred through the same fluid. It is described by:

$$Nu = \frac{hL\mathrm{c}}{k\,\mathrm{fluid}} \quad (5)$$

where k_{fluid} is the thermal conductivity of the fluid. A higher Nusselt number suggests that convective heat transfer is more effective. It is the key in the evaluation of heat transfer enhancement techniques.

2.3 The Boiling Curve in Quenching

Boiling heat transfer curve, which is far from linear, dominates the quenching process and happens when a part is rapidly cooled in a liquid medium. The boiling curve has three stages and is a popular way of describing the relationship between the part's surface temperature and the heat flux. Because enhancement techniques are specifically made to regulate the stages and control the outcome of quenching, understanding the boiling curve is thus necessary.

- **Stage A (Film Boiling - Vapor Blanket Stage):** Following the initial immersion, the liquid quenchant is immediately vaporized by the hot metal surface, forming a stable vapor film that completely encases the part. This vapor blanket acts as an insulator due to its low thermal conductivity, eventually slowing and stabilizing the cooling rate. This is usually an undesirable stage, and a primary goal of enhancement is to shorten or eliminate it.
- **Stage B (Nucleate Boiling - Transport Cooling Stage):** As the surface cools, the vapour film becomes unstable before eventually collapsing. The liquid makes direct contact with the surface, leading to the explosive formation and departure of vapour bubbles. This violent agitation and the absorption of latent heat of vaporization results in a very high heat transfer rate. This is the fastest cooling stage. It is responsible for forming hard microstructures like martensite.
- **Stage C (Convective Cooling - Liquid Cooling Stage):** Once the temperature of the surface drops below the quenchants' boiling point, all boiling ceases. Heat is then removed by natural or forced convection. This stage has a much slower cooling rate than nucleate boiling.

The figure below shows the boiling curve in quenching:

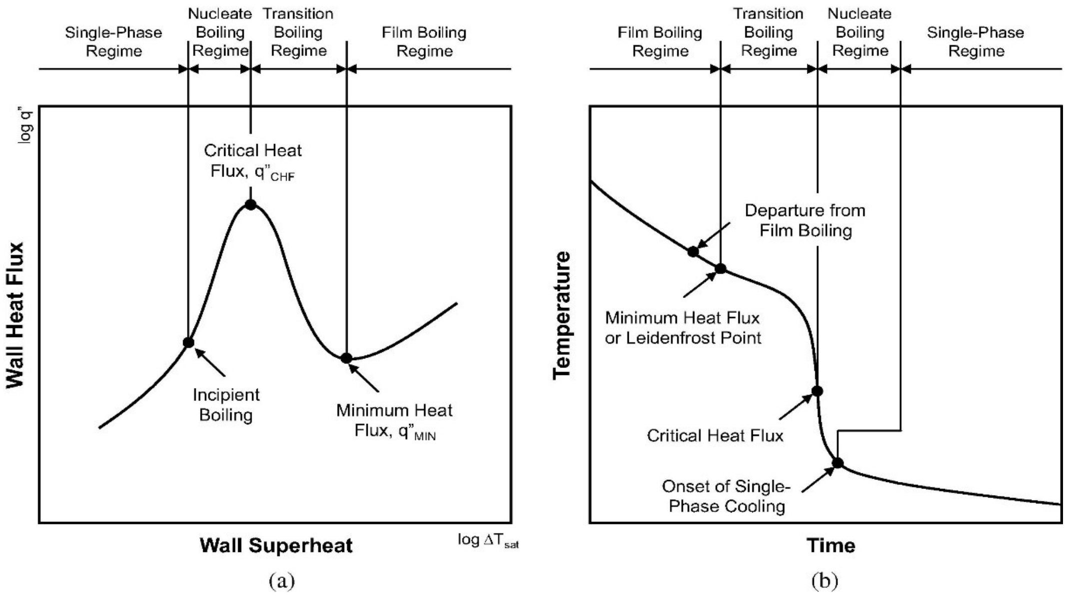

Figure 1: (a) Pool boiling curve and (b) quench curve [21]

3 Classification of Heat Transfer Enhancement Methods

The methods developed to improve heat transfer are numerous and varied. To clearly review and compare them, it is useful to group them into established categories. The most used classification, divides these techniques into three major groups: passive, active and compound techniques. This division is based on whether or not the method requires direct application of external power.

3.1 The Passive Techniques

Passive techniques enhance heat transfer without needing external power. They achieve this by modifying the system's geometry or the working fluid. These methods are generally favoured because they are simpler, yet reliable.

- **Modified Surfaces:** The surface of a metal part can have a significant effect on the heat transfer. Roughened surfaces increase the total surface area and create turbulence in the fluid boundary layer. This will lead to enhanced heat transfer by convection. In quenching, specifically designed surface modifications can encourage early transition from film boiling to nucleate boiling by increasing the density of nucleation sites [8]. Research has shown that applying a thin, porous oxide layer to a surface before quenching can drastically reduce the duration of the film boiling stage, resulting in a more uniform and faster quench. In high-temperature furnaces, applying coatings with high emissivity can increase the rate of heat absorption by radiation [9]. The major disadvantage of this method is the durability of the surface modification because there is the tendency for it to get degraded over multiple thermal cycles.
- **Fluid Additives (nanofluids):** This technique involves modifying the thermophysical properties of the working fluid. The development of nanofluids, which are manufactured colloids of nanoparticles (usually metals, oxides like Al_2O_3, or carbon nanotubes) suspended in a base fluid like water or oil, is the most studied contemporary example. It has been demonstrated that these nanoparticles increase the base fluid's thermal conductivity and, more crucially, in quenching, they stop a stable vapour blanket from forming, which raises the critical heat flux and speeds up cooling [10, 11].
  Numerous studies have explored the effect of nanofluids in quenching. Research using water-based Al_2O_3 nanofluids has demonstrated a significant increase in the critical heat flux (CHF), which marks the upper limit of the highly efficient nucleate boiling regime [11]. In practical applications, this translates to faster cooling rates. The maximum cooling rate of CK35 steel quenched in a diluted TiO_2

nanofluid was significantly higher than that of pure water, according to a study on the subject [12]. This was enough to produce a totally martensitic microstructure in the outer layer of the steel [12]. [13] found that smaller TiO_2 nanoparticles in water-based solutions shortened the full film phase, hastening the onset of nucleate boiling. In spite of its efficacy, obstacles like high production costs, potential environmental impact, and long-term stability of nanofluid suspensions must be addressed before nanofluids can have broad industrial adoption [10].

3.2 The Active Techniques

Active techniques require the application of external energy to manipulate the fluid flow and improve heat transfer, in spite of their complexity and cost, they offer greater control and a higher degree of enhancement than passive methods.

- **Mechanical Aids:** This is the most common active method used in industrial heat treatment. It involves using external power to drive pumps, stirrers, or propellers to induce forced convection in a quench bath. The resulting fluid agitation increases the effective velocity of the quenchant over the part's surface, which increases the heat transfer coefficient (h) and helps to physically break down the vapour film during the initial stage of quenching [3, 5].
- **Jet Impingement:** In this technique, a high-velocity jet of fluid is directed perpendicularly onto the surface of the component. By thinning the thermal boundary layer and creating intense turbulence at the point of impact, Jet impingement provides very high local heat transfer coefficients. The heat transfer decreases radially outwards, but is highest at the stagnation point (directly under the jet) [14]. It is used for both rapid heating (gas jets) and rapid cooling (liquid jets) and offers excellent control over which specific areas of a part are treated [15]. This method offers great control over both the location and intensity of cooling, making it ideal for applications such as selective surface hardening of gears and shafts. Uniform cooling can be attained on larger surfaces, by arranging arrays of jets. For example, studies on the cooling of hot steel plates with arrays of water jets have reported heat transfer coefficients (h) above 50,000W/m^2K, an order of magnitude much higher than conventional immersion or pool quenching [15].
- **Use of External Fields:** In order to control the fluid or surface, external fields are used. Ultrasonic agitation is a well-known example. Cavitation and acoustic streaming occur when high-frequency sound waves are injected into a quench bath. Extremely rapid and uniform cooling results from the sudden collapse of cavitation bubbles at the part's surface, which totally interrupts the film boiling stage [16]. Other techniques include controlling polar fluids or magnetic particles suspended in the quenchant by using electric or magnetic fields. According to Abed et al. (2023), depending on operating conditions, the presence of an ultrasonic field can boost the cooling rate by up to 133% by improving the material's overall heat transfer coefficient [17].

3.3 The Compound Techniques

Compound enhancement techniques involve using two or more of the techniques mentioned earlier, concurrently. The aim is to attain an overall enhancement which surpasses the combined effects of the individual methods. For instance, one could utilize a nanofluid (passive technique) within an ultrasonically stirred bath (active technique) to merge the advantages of improved fluid characteristics with the strong mechanical disruption of the boundary layer. The design and enhancement of compound methods constitute an important research field today, as they offer substantial control over rates of heat transfer unlike the passive and active techniques.

4 Comparative Analysis and Applications

No single heat transfer enhancement technique is optimal for all situations. The choice would depend on the material, the shape/geometry of the component, the required attributes and cost factors. Table 1 below presents a summary of comparison.

Table 1. Comparison of Heat Transfer Enhancement Techniques.

Technique	Mechanism	Effectiveness	Advantages	Limitations	Ideal Application	Reference
Nanofluids (Passive)	Nanoparticle deposition, improved fluid properties	Moderate	Passive, uniform cooling for complex shapes	High cost, fluid stability issues, environmental concerns	Immersion quenching of high-value, complex parts	[10], [11], [21]
Surface Modifications (Passive)	Increased nucleation sites, vapor film disruption	Low–Moderate	Passive, low cost	Durability issues, may not be reusable	Single-use or specific component treatments	[3], [9]
Ultrasonic Agitation (Active)	Acoustic cavitation, micro-jetting	High	Eliminates film boiling, uniform cooling for complex geometries	High initial equipment cost, energy consumption	Quenching of intricate or high-hardenability parts	[16], [17], [18]
Jet Impingement (Active)	Boundary layer thinning, high turbulence	Very High	Extremely high local heat transfer coefficient, controllable	Complex setup, potential for non-uniformity	Selective surface hardening, rapid plate/strip cooling	[15], [19], [20]
Compound Techniques (Active + Passive)	Combined mechanism of active & Passive techniques	Super/highly effective than others	Super/highly advantageous than others	High cost	Multiple/general applications	[6], [4], [8]

The comparison highlights the need for a compromise between performance, control, and cost. Passive methods like surface modifications and nanofluids have shown the ability to improve heat transfer rates and cooling uniformity, which is valuable in immersion or pool quenching of complex components. They are also attractive because they can be introduced into existing quench systems with minimal modification through retrofitting. Surface modifications, in particular, offer a quite stable and low-maintenance approach, because once they do not depend on consumable additives once they have been applied, and they can enhance nucleation behaviour at the fluid-solid interface. Combining nanoparticles with surface modifications can also improve the boiling performance, however, nanoparticles may get trapped on the surfaces, leading to deactivation of the nucleation sites [21]. However, practical use of nanofluids at industrial scale is still developing, as challenges like nanoparticle stability, long-term performance, and material costs would still need to be addressed.

In contrast, active methods such as ultrasonic agitation and jet impingement allow for a much higher degree of control over the cooling process. This gives engineers room to aim at specific sections of a workpiece for precise thermal management. This makes the active methods ideal for precision hardening of parts that require a high degree of dimensional accuracy and microstructural consistency like gear teeth, turbine blades and thin-gauge steel plates. These benefits however come at a higher cost because active systems typically call for more maintenance, energy, and equipment, making them more capital intensive. Passive approaches such as surface modifications or nanofluids on the other hand, generally involve relatively lower cost as they can be retrofitted into existing systems. However, their performance is less flexible and long-term operating costs can still accumulate for nanofluid enhancements.

For Nigeria's iron and steel sector, particularly in establishments such as Ajaokuta Steel Company, Delta Steel Complex, and local foundries, embracing advanced methods like jet impingement and ultrasonic-assisted quenching would be a step in the right direction towards boosting efficiency and creating value. By promoting the local production of precision hardened parts with high performance for the oil and gas, automotive, and agricultural machinery industries and manufacturing sectors, this would increase local manufacturing and lessen our reliance on imported materials. This would in turn reduce our reliance on imported components and create opportunities to compete internationally.

Nevertheless, the selection of these enhancement techniques should be determined by cost–benefit evaluation, and assessing the availability of existing infrastructure. Although active systems need a higher upfront investment in control systems, pumps, or ultrasonic generators, they can shorten cycle times, improve product quality, and reduce post-process machining, which could eventually lead to reduced operating costs. Combining these methods with modern digital monitoring, AI driven process management and predictive control systems would make production processes more repeatable and boost energy efficiency. This would then result in making our Nigerian metallurgical products much more attractive and competitive in global markets.

5 Conclusion

Heat transfer enhancement techniques used in metals heat treatment are categorized into passive, active, and compound methods. The comparison in this review shows a compromise between cost, complexity, and performance. Passive techniques, such as nanofluids and surface modifications, offer relatively low-cost, retrofittable improvements suitable for pool quenching and other general quenching purposes. Active techniques, including jet impingement and ultrasonic agitation, give higher control, allowing precision hardening and reducing the distortion in critical components. Compound approaches although not widely implemented, have a lot of potential for achieving performance improvements in synergy. The adoption of advanced heat transfer enhancement methods would definitely serve as a catalyst for industrial value addition for the Nigerian metallurgical industry. To implement these successfully, however, a step-by-step approach is required, starting with pilot projects, facility checks and small-scale trials before intentional integration at the high-level industries. Investing in skills development, local fabrication of enhancement equipment, and modern process monitoring systems will also be needed alongside, to maximize the return on investment. More research would also need to be carried out to fast-track the implementation of modern technologies such as hybrid fluids and nanostructured coatings, with the integration of artificial intelligence and smart systems. Durability, environmental impact, quantitative performance data, and socioeconomic issues unique to Nigeria must also be considered.

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