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Optimizing Rice Heating Efficiency: A Comparative Study of Zigzag Rail Design and Hybrid Induction Heating in a Novel Rice Heating System

***Abstract**. This article outlines the development of a novel rice heating system, leveraging induction heating technology and hot air for enhanced efficiency. The core innovation lies in a rectangular pipe featuring three types of alternating zigzag rails, set at angles of 35, 45, and 55 degrees, to optimize hot air flow and test efficiency. The design process involved using Solidwork program to simulate hot air flow, followed by real-world experiments to validate the simulation outcomes. Key performance indicators included the temperature of rice grains exposed to hot air and the effectiveness of induction heating in uniformly heating the rice without causing damage or breakage. The study also compared the effectiveness of using hot air alone versus a combination of hot air and induction heating. Rice flow rates were tested at 100kg/h, 150kg/h, and 200kg/h, with corresponding hot air power levels of 1,143W, 2,352W, and 3,756W, and induction heating powers of 146W, 228W, and 360W. An infrared thermometer measured the rice temperature. Results indicated that the 45-degree zigzag rail design yielded higher rice temperatures without damage. Additionally, combining hot air with induction heating was found to increase rice temperature more effectively and use energy more efficiently compared to using hot air alone.*

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Streszczenie.** W tym artykule opisano rozwój nowatorskiego systemu ogrzewania ryżu, wykorzystującego technologię ogrzewania indukcyjnego i gorące powietrze w celu zwiększenia wydajności. Główna innowacja polega na prostokątnej rurze z trzema typami naprzemiennych szyn zygzakowatych, ustawionych pod kątem 35, 45 i 55 stopni, w celu optymalizacji przepływu gorącego powietrza i testowania wydajności. Proces projektowania obejmował użycie programu Solidwork do symulacji przepływu gorącego powietrza, a następnie eksperymenty w świecie rzeczywistym w celu walidacji wyników symulacji. Kluczowe wskaźniki wydajności obejmowały temperaturę ziaren ryżu wystawionych na działanie gorącego powietrza i skuteczność ogrzewania indukcyjnego w równomiernym ogrzewaniu ryżu bez powodowania uszkodzeń lub łamania. W badaniu porównano również skuteczność stosowania wyłącznie gorącego powietrza w porównaniu z kombinacją gorącego powietrza i ogrzewania indukcyjnego. Przepływ ryżu testowano przy 100 kg/h, 150 kg/h i 200 kg/h, przy odpowiednich poziomach mocy gorącego powietrza 1143 W, 2352 W i 3756 W oraz mocy grzania indukcyjnego 146 W, 228 W i 360 W. Termometr na podczerwień zmierzył temperaturę ryżu. Wyniki wskazały, że 45-stopniowa konstrukcja szyny zygzakowatej zapewniała wyższą temperaturę ryżu bez uszkodzeń. Ponadto stwierdzono, że połączenie gorącego powietrza z ogrzewaniem indukcyjnym zwiększa temperaturę ryżu bardziej efektywnie i wykorzystuje energię bardziej efektywnie w porównaniu z użyciem wyłącznie gorącego powietrza.* (Optymalizacja efektywności ogrzewania ryżu: Studium porównawcze konstrukcji szyny zygzakowatej i hybrydowego ogrzewania indukcyjnego w nowym systemie ogrzewania ryżu***)

Keywords: Induction Heating, Rice Heating System, Zigzag Rail Design, Hybrid Systems
Słowa kluczowe: Ogrzewanie indukcyjne, system ogrzewania ryżu, konstrukcja szyny zygzakowatej, system hybrydowy

1. **Introduction**

Grains like wheat, rice, and maize hold a central position in the global food security framework and economy, serving as the cornerstone of diets and major commodities in international trade. Their cultivation and production have far-reaching implications, not only in terms of nutritional sustenance for the global population but also in the context of environmental sustainability. Key challenges in grain production include efficient water usage and adapting to the impacts of climate change. The technological evolution in agriculture, therefore, plays a pivotal role in enhancing the efficiency of grain production, making these crops indispensable in global food systems. In the cycle of grain production, post-harvest preservation emerges as a critical step for ensuring year-round availability and preventing loss. Among various preservation methods, drying stands out as a fundamental process. It effectively reduces spoilage, inhibits mold growth, and curtails the development of toxins before the produce is transformed into diverse food products [1-10]. This process is not just about moisture removal; it's about safeguarding the quality and safety of food supplies. The methods employed for drying agricultural produce are varied, each with its own set of benefits and challenges. Traditional approaches, such as using natural sunlight, have been commonplace due to their simplicity and low cost. This method capitalizes on converting the sun's heat energy into a means for drying grains [11]. However, its efficacy is highly dependent on weather conditions, limiting its reliability and applicability [12]. As agricultural practices have evolved, so have the drying methods. Modern approaches have sought to overcome the limitations of traditional methods, leading to the exploration and adoption of alternative techniques. One such method involves using heating coils, where electrical energy is used to heat a coil, which then transfers the heat to the material to be dried [13]. While effective, this method is not without its drawbacks, primarily its relatively high energy consumption, which can be a significant factor, especially in large-scale operations [14]. Another technique is gas heating, which involves generating heat to evaporate moisture within metals, subsequently transferring the heat to the agricultural produce [15]. This method, while efficient, necessitates more complex equipment compared to natural or coil heating methods and also carries implications due to combustion [16]. Amidst these varied techniques, the use of electromagnetic fields as a heat source has emerged as a modern, innovative approach#[17-19]. This technology, characterized by energy efficiency, safety, and ease of temperature control, marks a significant advancement in the field of agricultural produce drying. Currently, this technology is employed in two principal forms: induction heating and dielectric heating [20-27]. The architecture of energy emitters has evolved, incorporating various designs for diverse applications#[28-34]. Both methods have garnered attention for their potential to offer sustainable and efficient alternatives to traditional drying techniques.

Induction heating, particularly, has shown promise in drying processes [35-36]. Operating on the principle of electromagnetic induction, this method involves passing an alternating current through a coil to create a rapidly alternating magnetic field. When a conductive material, like metal, is placed within this magnetic field, eddy currents are induced within the material. These currents generate heat due to the resistance of the material, which is then transferred to the surrounding agricultural produce, enabling efficient and uniform drying.

Dielectric heating, also known as radio frequency (RF) or microwave heating, offers a different approach [37]. This process utilizes high-frequency electromagnetic waves, typically in the radio frequency or microwave spectrum, to heat dielectric materials. The waves cause rapid oscillation of polar molecules, such as water, generating heat through internal friction and dipole rotation. This method is particularly effective for applications requiring even heat distribution and is highly efficient for quickly heating materials. Enhancing the efficiency of dielectric heating is a topic of ongoing research. A promising strategy involves pre-heating the raw materials before they are subjected to the dielectric heating process. Research by Nelson and others has shown that increasing the temperature of the raw materials can enhance their dielectric properties, thus boosting the efficiency of dielectric heating in both effectiveness and time reduction. The versatility of dielectric heating extends to various applications within the agricultural sector. Its use is not limited to the drying of crops; it also includes pest control and disinfestation, seed germination and sterilization, herbicide activation, and other post-harvest processes. These applications are particularly relevant for maintaining product quality and safety, especially in the processing of fruits and vegetables.

Given the significance of these findings, this research proposes an in-depth investigation into the design of an induction heating system, specifically for heating rice, which has been selected as the sample material. The study aims to evaluate the power levels involved in using hot air in conjunction with induction heating and compare this with the use of hot air alone. Furthermore, the research seeks to assess the heating efficiency at various rice flow rates, employing both simulations of wind flow in rice conveyor pipes and practical usage tests.

The methodology employed in this research is detailed in Section 2, where the experimental setup, including the induction heating system design and the simulation models used, will be described. Section 3 will present the results and discussions, elaborating on the findings from both the simulations and the actual usage tests. This section will also include a comparative analysis of the efficiency of the heating methods under different operational conditions. Finally, Section 4 will offer a comprehensive summary of the research findings, highlighting the implications of these findings for the agricultural industry and suggesting areas for future research.

2. Materials and Methods

This section outlines the methodology adopted for the experimental study, focusing on the design and setup of the apparatus, the materials used, and the procedures followed. The experimental setup is designed to evaluate the efficiency of induction heating in combination with hot air for heating rice grains. The entire system is segmented into three major components: the induction heating circuit, the rice flow pipe, and the hot air blowing mechanism.

Induction Heating Circuit: Central to the experiment is the induction heating circuit, which is engineered to provide a variable power range from a minimum of 100W to a maximum of 2500W. This variability allows for a comprehensive analysis of the effect of different power levels on the heating process. The heart of this circuit is the induction coil, meticulously crafted from a copper wire with a diameter of 3 mm. This coil, constituting 30 turns with a consistent 3 cm spacing between each wire, is strategically coiled around the rice flow pipe. The total inductance of the coil, calculated to be approximately 90 uH, is determined through precise resonance matching calculations. This inductance is critical as it directly influences the efficiency and effectiveness of the induction heating process.

Rice Flow Pipe Design: The rice flow pipe is ingeniously designed to facilitate the optimal flow and heating of rice grains. It features an interior structure comprising alternating zigzag flow troughs, each extending to a length of 15 centimeters. These troughs, comprising five panels, are arranged to guide the rice flow at a 45-degree angle, a configuration determined to be most effective based on preliminary studies. The dimensions of the pipe are carefully chosen to optimize the heating process – it measures 100 cm in length, 20 cm in width, and 6 cm in thickness, and is constructed from 3 mm thick steel. This material choice not only ensures durability but also plays a vital role in the induction heating process due to its conductive properties. The upper section of the pipe is conically shaped, serving as the entry point for the rice. This section includes a specialized mechanism designed to regulate the descent of rice into the pipe, ensuring a consistent and controlled flow.

Hot Air Blowing Mechanism: The hot air system is a pivotal component of the experimental setup. It consists of a blower capable of delivering air at a speed of 16.3 m/s. This air is directed into the lower left entry of the pipe, ensuring an even distribution of hot air throughout the pipe's length. The system is calibrated to operate at three distinct air temperatures – 40°C, 60°C, and 80°C. These temperatures correspond to power settings of 1,143W, 2,352W, and 3,756W, respectively. The choice of these specific temperature and power settings allows for a thorough investigation of the impact of different levels of hot air heating on the rice grains.

Experimentation Procedure: The experimentation involves adjusting rice flow rates to 100 kg/h, 150 kg/h, and 200 kg/h. These variations are essential to evaluate the heat transfer efficiency from the hot air to the rice grains under different flow conditions. Comparative experiments are conducted to assess the temperature increments in the rice grains when heated solely by the hot air system versus a combination of hot air and induction heating. This comparative analysis is crucial to understanding the added value of induction heating in the process.

Induction Heating Power Settings: To analyze the efficacy of power transfer through induction heating, the induction heating power is set at three different levels – 146W, 228W, and 360W. These levels are chosen to represent a range of low, medium, and high-power settings, providing a comprehensive understanding of how varying levels of induction heating influence the heating process. These settings are maintained consistently across different rice flow rates to ensure a fair and accurate comparison with the temperature increments achieved through the standalone hot air system.

2.1 Induction Heating system.

Induction heating is a fascinating and efficient process used for heating conductive materials, most commonly metals. It relies on the principles of electromagnetic induction to generate heat directly within the workpiece. Unlike traditional heating methods, induction heating offers rapid, controllable, and localized heating without any physical contact between the heat source and the material being heated. The fundamental principle behind induction heating is Faraday's Law of Electromagnetic Induction, which states that a changing magnetic field within a circuit induces a current in the circuit. Mathematically, this is expressed as:

(1) $$\varepsilon = -N\frac{d\Phi}{dt}$$

Where ε is the induced electromotive force (EMF) in volts, N is the number of turns in the coil, and $d\Phi/dt$ is the rate of change of magnetic flux in webers per second.

In an induction heating system, an alternating current (AC) flows through a coil, producing a dynamic magnetic field around it. When a conductive material is placed within this magnetic field, the changing field induces eddy currents in the material. According to Lenz's Law, these currents flow in such a way as to create their own magnetic field, which opposes the original field. The resistance of the material to the flow of these eddy currents generates heat, which is given by Joule's Law:

(2) $$P = I^2R$$

where P is the power (heat) generated in watts, I is the induced current in amperes, and R is the resistance of the material in ohms.

The efficiency of induction heating is influenced by several factors, including the frequency of the alternating current, the properties of the material (such as permeability and resistivity), and the design of the induction coil. Higher frequencies can produce more concentrated heating and are better suited for smaller or thinner materials. The coil design also plays a critical role in determining the distribution of the magnetic field and, consequently, the heating pattern.

Induction heating has diverse applications, ranging from industrial forging and melting to domestic cooking appliances. Its ability to provide rapid, controlled, and efficient heating makes it a valuable technology in numerous fields.

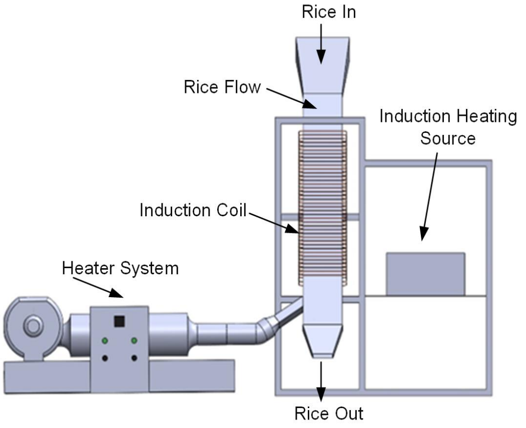

Fig 1: Schematic Representation of the Heating System Configuration

2.3 Heat transfer.

The theory of heat energy transfer to grains during the hot air drying process is fundamentally based on the principles of thermodynamics and heat transfer. The primary mode of heat transfer in this process is convective heat transfer, where heat is transferred from the hot air to the grains. The basic heat transfer equation that governs this process is given by:

(3) $$q = hA\left(T_{air} - T_{grain}\right)$$

where: q is the rate of heat transfer (in watts, W). h is the convective heat transfer coefficient (in watts per square meter per degree Celsius, $W/m^2\,°C$). A is the surface area of the grain exposed to the hot air (in square meters, m^2). Tair is the temperature of the hot air (in degrees Celsius, $°C$). Tgrain is the temperature of the grains (in degrees Celsius, $°C$).

This equation highlights that the rate of heat transfer (q) is directly proportional to the temperature difference between the hot air and the grains ($T_{air} - T_{grain}$), the surface area of the grains exposed to the hot air, and the convective heat transfer coefficient.

Key Aspects of the Process:

Convective Heat Transfer: Convective heat transfer is the primary mechanism through which the hot air transfers its energy to the grains. The convective heat transfer coefficient (h) is influenced by factors such as air velocity, properties of the air (like viscosity and thermal conductivity), and the configuration of the grain bed.

Temperature Gradient: The effectiveness of the drying process depends significantly on the temperature gradient between the hot air and the grains. A larger temperature difference typically results in more efficient drying.

Moisture Evaporation: As the grains absorb heat, their temperature increases, causing the moisture within them to evaporate. The energy required for this phase change comes from the heat transferred from the hot air, which is used to overcome the latent heat of vaporization of water.

Grain Properties: The thermal properties of the grains, including specific heat, thermal conductivity, and density, affect how heat is absorbed and distributed within the grain. These properties can vary with the type of grain and its initial moisture content.

2.4 Statistical Analysis.

In this research, three replicates of the experiment were carried out, and the gathered data was subjected to statistical analysis using SPSS Statistics, version 20.0. To evaluate the statistical disparities among the means of the various samples, a one-way Analysis of Variance (ANOVA) was employed, setting the threshold for statistical significance at 5%. The study focused on discerning significant differences in the dielectric properties of the tested soil samples, utilizing Fisher's Least Significant Difference (LSD) test as the criterion for significance.

3. Results and discussions

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3.1 Simulations Result and. Discussions

This research was embarked upon with the primary objective of augmenting the efficiency of power transfer to rice grains during their transit through a delivery pipe. Recognizing the potential for improvement in this domain, the study was geared towards exploring various flow patterns by altering the trough angle within the pipe. This approach was underpinned by the hypothesis that different trough angles could significantly influence the heat exposure and, consequently, the quality of the rice grains during processing. To bring this conceptual idea to fruition, SolidWorks – a state-of-the-art simulation software known for its precision and versatility – was employed. The use of such sophisticated software was integral to the study, as it allowed for a detailed and accurate representation of the airflow dynamics within the pipe, as well as the distribution of hot air, which is a critical factor in the heating process of the rice grains.

The investigative process was structured around three distinct simulation models. Each of these models was characterized by a specific trough angle – 35 degrees, 45 degrees, and 55 degrees. This range of angles was chosen to provide a comprehensive understanding of how varying degrees of inclination could impact the heating process. To ensure consistency and reliability in the results, all models were assessed under uniform operational conditions. These conditions included a wind speed of 16.3 meters per second parameters that are representative of typical industrial settings for rice processing.

The simulation outcomes, which are visually detailed in Figures 2-4, offered insightful revelations. At a 35-degree trough angle, it was observed that the rice grains moved most rapidly from the top to the bottom of the pipe. This quick movement implied that the grains were exposed to the least amount of heat. While this might seem advantageous in preventing overheating, it also raised concerns about the grains not receiving adequate heat treatment, which is essential for certain quality parameters in rice processing.

In contrast, the simulation model with a 45-degree trough angle presented a markedly different scenario. The rice grains in this model moved more slowly compared to the 35-degree model. This reduced speed of movement meant that the grains were exposed to the hot air for a longer duration, thereby receiving more effective heat treatment. This observation was particularly noteworthy as it suggested that a moderate slowing of the grain movement could enhance the heating process without compromising the quality of the rice grains.

The model with a 55-degree trough angle offered another perspective. Here, the movement of the rice grains was the slowest among the three models, leading to the maximum heat exposure. While, theoretically, this should have been the most effective in terms of heat treatment, the reality was somewhat different. The prolonged exposure to heat at this angle resulted in damage to the grains due to overheating. This finding was critical as it highlighted the fine balance that needs to be maintained in the heating process – too little heat exposure could result in underprocessing, while too much could cause damage to the grains. From these observations, the study concluded that the 45-degree trough angle struck the most effective balance. This angle facilitated efficient heat exposure while simultaneously ensuring that the integrity and quality of the rice grains were not compromised. Such a balance is not merely a technical achievement but is of paramount importance in the context of rice processing industries. It addresses a critical need for optimizing energy use while maintaining, if not enhancing, the quality of the processed rice.

Furthermore, these findings have broader implications. They underscore the importance of precision in the design and operation of grain processing equipment. The study clearly demonstrates that even minor adjustments in the equipment design, such as the angle of the trough, can have significant impacts on the efficiency of the process. This insight opens up new avenues for innovation in the design of grain processing machinery, where efficiency and quality are pivotal considerations.

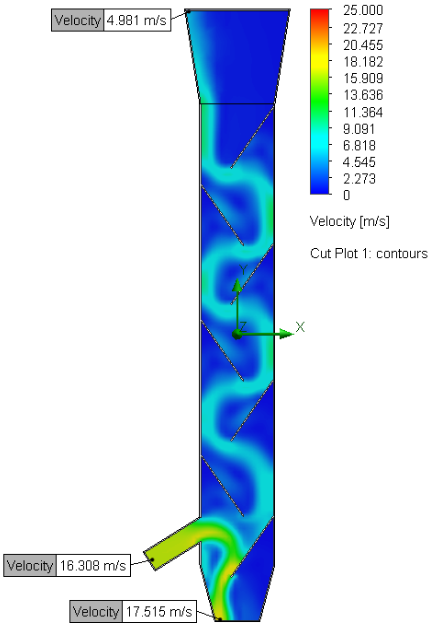


Fig. 2: displays a simulation of the rice flow trough pattern set at a 35-degree angle.

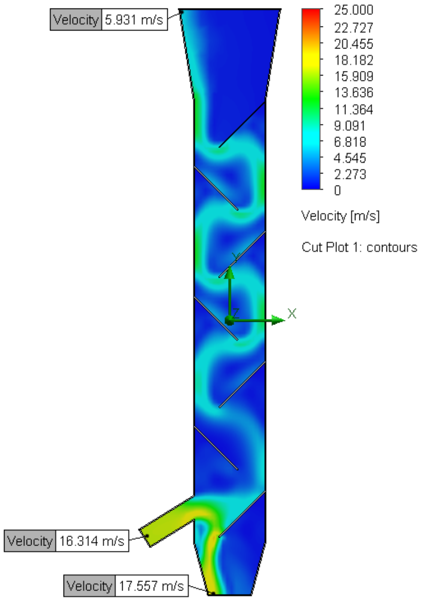


Fig. 3: displays a simulation of the rice flow trough pattern set at a 45-degree angle.

The comprehensive analysis of how different trough angles in a rice delivery pipe affect the efficiency of heat treatment of rice grains. The optimal angle of 45 degrees offers a practical solution that balances effective heat exposure with grain integrity, thereby enhancing the overall efficiency of the rice conveyance system. These findings are not only significant for the rice processing industry but also contribute to the broader field of agricultural processing, where efficiency and product quality are continually sought-after objectives.

3.2 Experiments Result and Discussions.

This study was primarily focused on enhancing the thermal efficiency of rice grain processing using a combination of hot air and induction heating. Set against the backdrop of varying operational conditions – including different grain flow rates and power settings – the experimental setup was meticulously designed to provide comprehensive insights. The critical findings, presented in Figures 6, 7, and 8, shed light on the interplay between power consumption and the resulting temperature increase in rice grains. These results not only offer a deeper understanding of the heating process but also suggest ways to optimize energy use in grain processing.

At a grain flow rate of 100 kg/h, the results, as depicted in Figure 6, reveal a notable contrast in heating efficiency between sole hot air usage and its combination with induction heating. Specifically, the application of 1,143W of hot air, when supplemented with 146W of induction heating, led to a temperature increase of 5.2 degrees Celsius. This enhancement was achieved with significantly lower total power consumption compared to using 2,523W of hot air alone, which only achieved a comparable temperature increase of 5 degrees Celsius. This suggests a marked efficiency improvement when incorporating induction heating, even at its lowest power setting.

Elevating the grain flow rate to 150 kg/h, as shown in Figure 7, the results followed a similar trend but with a slight reduction in the temperature increments. This indicates the influence of grain flow rate on the heating process. Even at this higher flow rate, combining hot air with induction heating remained more energy-efficient than using hot air alone. This finding underscores the importance of considering flow rates in industrial applications, as it directly impacts the heating efficiency and energy consumption.

Further increasing the grain flow rate to 200 kg/h, Figure 8 presents an intriguing scenario. The initial setting of 1,143W hot air power, complemented with 146W of induction heating, led to a temperature rise of 2.7 degrees Celsius – a notable increase from the 1.5 degrees Celsius achieved with hot air alone. The trend of enhanced efficiency at higher induction heating powers was consistent, reinforcing the argument for combining heating methods. These results also highlight the scalability of this approach in different operational settings.

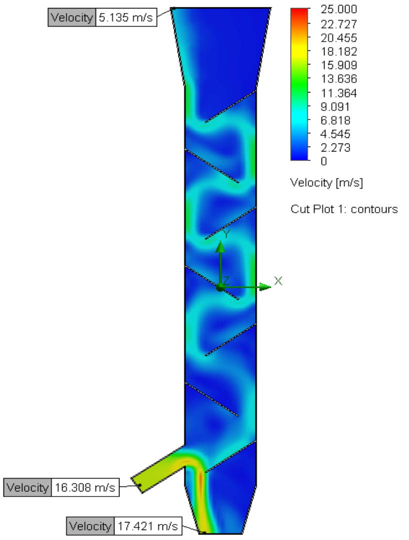


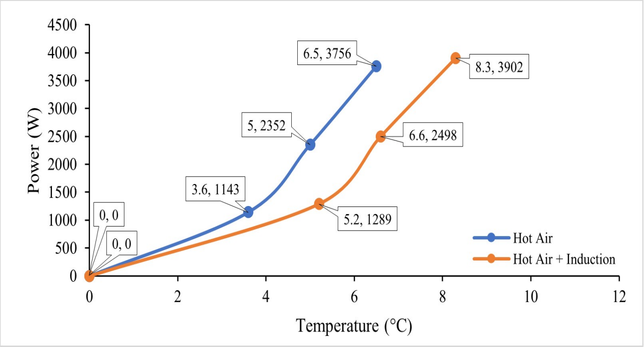
Fig. 4: displays a simulation of the rice flow trough pattern set at a 55-degree angle.

The experimentation clearly demonstrates that the combination of hot air and induction heating is not just a viable alternative but a superior method for heating rice grains. This hybrid approach significantly reduces the total power requirement while achieving equivalent or higher temperature increases in the grains. This efficiency gain is critical, especially in industrial settings where energy costs and consumption are major considerations. The synergy between hot air and induction heating seems to produce a more uniform and effective heating process, which is crucial for maintaining grain quality. This finding could be a game-changer for the rice processing industry, potentially leading to more sustainable and cost-effective practices.

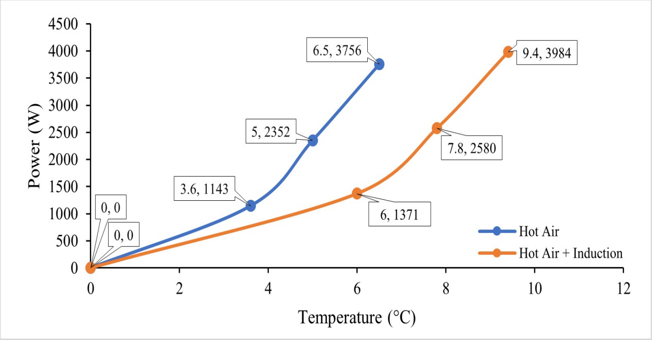
The grain flow rate emerges as a key factor influencing the heating efficiency in our experiments. As the flow rate increases, the effectiveness of the heating methods appears to fluctuate. This observation is vital for practical applications, as it suggests that optimal settings may vary based on operational throughput. Industries looking to implement these findings must consider their specific grain flow rates to achieve the best balance between energy consumption and heating efficiency. This aspect opens up avenues for further research, especially in exploring the upper limits of flow rates and their corresponding optimal heating conditions.

The implications of this study for the rice processing industry are substantial. By adopting the combination of hot air and induction heating, facilities can achieve higher efficiency in grain heating while reducing energy costs. The adaptability of this method to different grain flow rates also adds to its industrial appeal, offering a flexible solution to various operational scales.

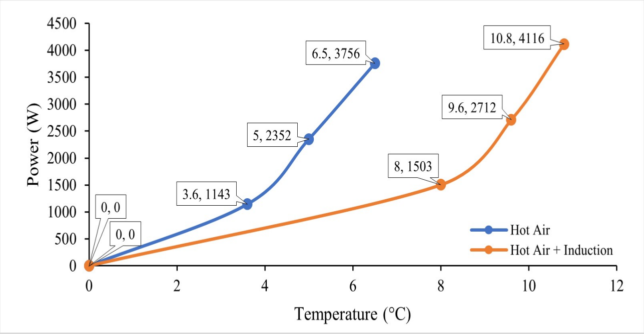
While the study provides insightful results, it is not without limitations. Future research could explore a broader range of grain types and environmental conditions to validate the universality of these findings. Additionally, long-term studies on the impact of this heating method on grain quality would be beneficial.



(a) depicting the scenario where 146W of power is utilized



(b) showing the results at 228W of power



(c) illustrating the temperature differences when 360W of power is employed.

Fig. 6: presents a comparative graph illustrating the variation in temperature when using hot air solely and when it is combined with induction heating at a flow rate of 100 kg/hr.

The integration of hot air and induction heating presents a promising advancement in rice grain processing, offering enhanced efficiency and energy savings. The results of this study not only contribute to a better understanding of grain heating dynamics but also pave the way for more sustainable practices in the industry. Continued exploration in this field is essential to further refine these methods and extend their application to broader contexts.

4. Conclusions:

This study conclusively demonstrates that a 45-degree zigzag rail design within a rice flow pipe significantly enhances the heating efficiency of rice grains by optimizing hot air flow and energy use. Furthermore, it establishes that combining hot air with induction heating is superior to using hot air alone for rice grain processing. This hybrid method not only achieves higher temperature increases in the# grains but also reduces total power consumption, showcasing a notable improvement in energy efficiency. The research underscores the importance of adjusting operational settings, such as grain flow rates, to optimize heating efficiency and energy consumption, indicating the need for flexible system design in industrial applications. The findings mark a significant advancement in rice processing technology, offering a more sustainable, efficient, and cost-effective method that could transform industry practices. Future investigations could further explore the applicability of these methods to different grain types and assess the long-term impact on grain quality, potentially broadening the scope and impact of this research in agricultural processing technology. This study's insights into optimizing rice heating efficiency pave the way for more sustainable practices in the agricultural sector, highlighting the importance of innovative approaches to improving food processing systems.

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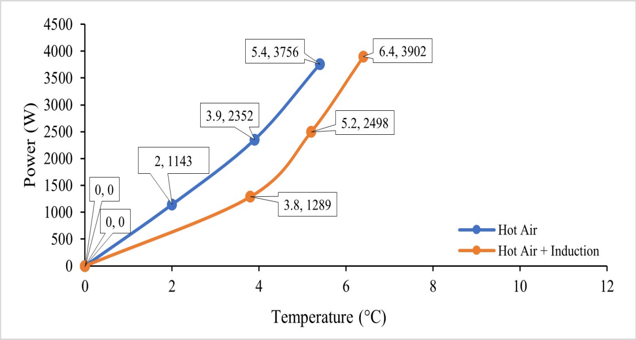

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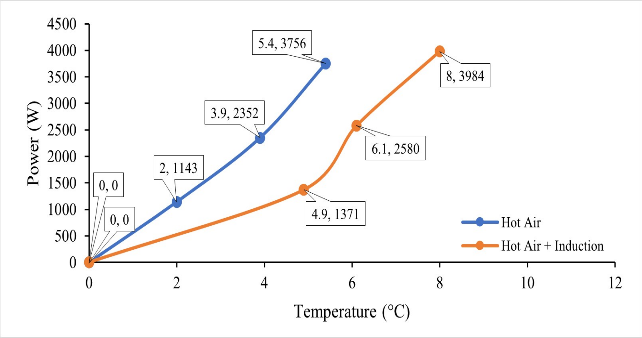
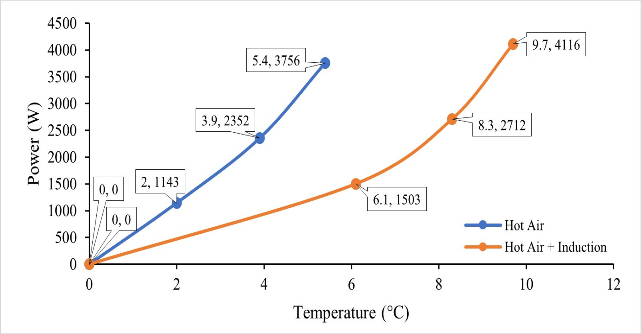
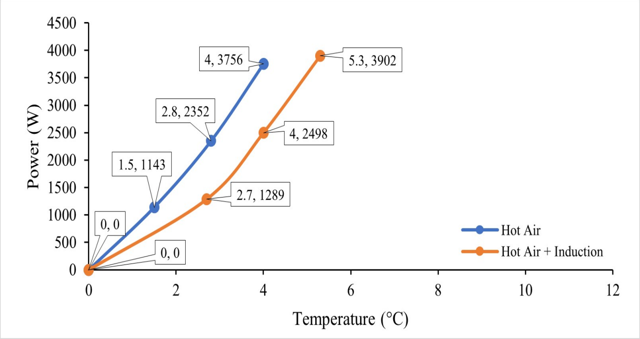


(b) showing the results at 228W of power

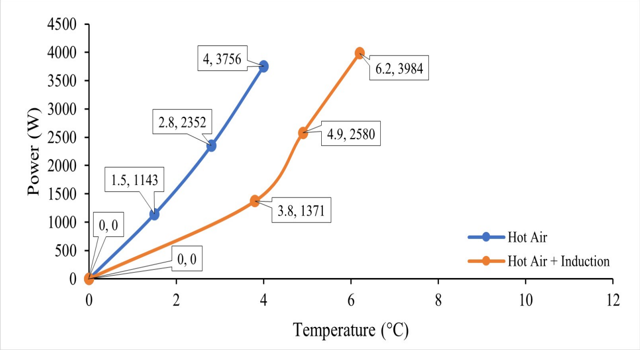


(c) illustrating the temperature differences when 360W of power is employed.

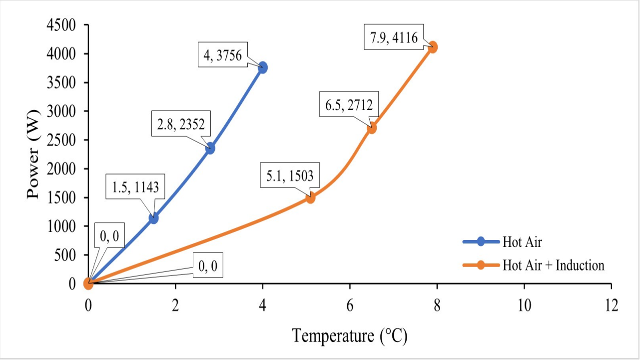
Fig. 7: presents a comparative graph illustrating the variation in temperature when using hot air solely and when it is combined with induction heating at a flow rate of 150 kg/hr.



(a) depicting the scenario where 146W of power is utilized



(b) showing the results at 228W of power



(c) illustrating the temperature differences when 360W of power is employed.

Fig. 8: presents a comparative graph illustrating the variation in temperature when using hot air solely and when it is combined with induction heating at a flow rate of 200 kg/hr.

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