Systematic Approach to Convert Industrial Electric Oven to Piped Natural Gas Oven to reduce environmental impact without impacting Process and product Performance

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Abstract: Industrial ovens are substantial energy consumers and play a crucial role in influencing product quality. Therefore, enhancing their performance should be a priority for manufacturers. This review outlines an innovative and actionable strategy for enhancing oven performance, with a focus on improving energy efficiency, optimising processes, and promoting environmental sustainability. The proposed approach is divided into three phases: gaining a deep understanding of the product, refining the production process, and optimising process parameters. Key parameters such as temperature, air flow rate, and cycle time are adjusted to achieve energy savings while minimising environmental impact.

Keywords: Process parameters, Performance improvement, Optimisation, Environmental Impact, Electric Oven, PNG Oven.

I. INTRODUCTION:

Optimising Manufacturing Lead Time, Energy Efficiency and Reducing Environmental Impact

Manufacturing companies continually seek to enhance operational efficiency and reduce production costs while improving customer satisfaction. One of the most critical performance indicators in achieving these goals is lead time, as it directly impacts both customer experience and internal operational expenses.

In discrete manufacturing, lead time improvements are typically achieved through ongoing process optimisation and investment in advanced machinery. However, in continuous manufacturing systems, where all operations are interdependent, the pace of production is determined by the slowest process. This constraint is especially evident in thermal treatment applications such as curing, which require materials to pass through long ovens that maintain precise temperatures over extended periods.

To accommodate faster production rates, these ovens must be lengthened, increasing both space and energy requirements. Yet, modifying or replacing this equipment is often prohibitively expensive. As a result, efforts to improve performance in such systems often focus on enhancing oven efficiency rather than expanding infrastructure.

Industries employ various types of heat treatment equipment, including furnaces, kilns, and convection ovens, to fulfil tasks like curing, drying, and baking. Convection ovens, which use hot air nozzles for heat transfer, are widely used due to their effectiveness. However, even high-performing ovens lose efficiency over time due to structural degradation, changing process demands, and technological obsolescence. This opens up significant opportunities for improvement, particularly in terms of energy efficiency and production throughput.

As component sizes shrink and product complexity increases, traditional heating systems struggle to meet evolving manufacturing needs. Consequently, there is growing interest in site-wide energy optimisation, particularly within heating processes. Large-scale retrofitting, however, presents challenges such as limited space, production disruptions, heat loss, outdated layouts, and high costs. A more feasible approach is to focus on energy reduction at the unit level, particularly within individual ovens, to improve sustainability without extensive facility upgrades.

Enhancing Industrial electric oven performance offers numerous benefits, including improved product quality, higher production efficiency, enhanced worker safety, reduced waste, and lower energy consumption. Understanding and controlling process variations is key to maintaining consistency, meeting safety standards, and reducing operating costs. These insights enable manufacturers to streamline workflows, minimise defects, lower scrap rates, and reduce transition times between product lines.

Industrial electric heating plays a central role in many sectors, including food processing, ceramics, metallurgy, and chemical manufacturing. Historically, Industrial electric ovens have been widely adopted for their precise temperature control, ease of use, and point-of-use efficiency. However, their environmental impact depends heavily on the Industrial electricity source. In regions where power is generated primarily from coal or other fossil fuels, Industrial electric ovens can have a substantial indirect carbon footprint, raising concerns about long-term sustainability.

In contrast, Piped Natural Gas (PNG) offers a more environmentally friendly and cost-effective alternative. PNG combustion generates significantly lower carbon dioxide emissions compared to coal-based Industrial electricity and also reduces pollutants such as sulfur oxides, nitrogen oxides, and particulates. A robust pipeline network; PNG provides a reliable and continuous energy supply well-suited for Industrial electric applications.

Converting Industrial electric ovens to PNG-powered systems presents a compelling opportunity for manufacturers to lower both operating costs and carbon emissions. While this transition requires initial investments in burners, pipelines, and safety infrastructure, the long-term benefits, particularly in regions with carbon-intensive Industrial electricity grids, can be substantial. The move supports sustainable heating practices and aligns with broader environmental and economic goals.

This paper explores the technical considerations involved in transitioning Industrial electric ovens to PNG, evaluates the environmental and economic advantages, and examines how such conversions can support the development of sustainable Industrial electric heating systems.

II. Technology And Process Mechanism Of Industrial Electric Oven & Fuel-Fired Ovens

Industrial electric ovens are engineered systems designed to provide controlled heating for processes such as baking, drying, curing, sintering, annealing, or surface treatment. They operate on the principle of **heat transfer** conduction, convection, and radiation to raise the temperature of the material uniformly to achieve the desired physical or chemical transformation. The technology of Industrial electric ovens can be classified broadly into **Industrial electric resistance ovens** and **fuel-fired ovens** (e.g., using Piped Natural Gas, LPG, or oil).

1. Basic Components of an Industrial Electric Oven

- **Heating System:**
  - *Industrial electric ovens* use resistance heating elements to convert electricity directly into heat with near 100% efficiency at the point of use.

- *Gas-fired ovens* employ burners to combust fuel, producing hot gases that transfer heat by convection and radiation.

- **Insulation and Chamber:** High-grade refractory or ceramic fibre insulation minimises heat loss and ensures stable temperature control.
- **Air Circulation System:** Fans and ducts regulate airflow, ensuring uniform heat distribution within the chamber.
- **Control System:** Thermocouples, programmable logic controllers (PLC), and automated safety devices regulate temperature, timing, and fuel flow.
- **Exhaust and Safety Systems:** Ventilation removes combustion gases, moisture, or volatile organic compounds (VOCs) from the chamber.

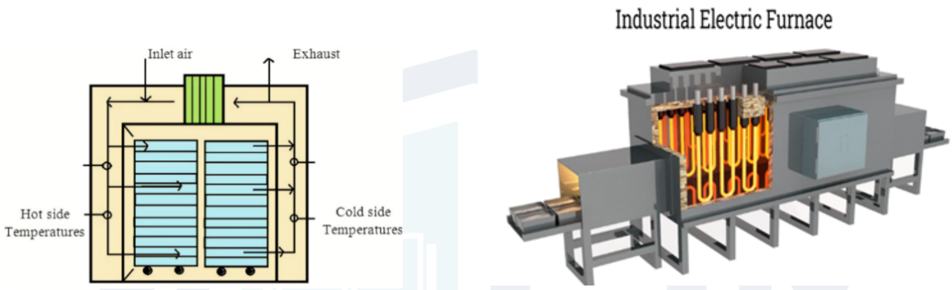


Figure1. Schematic diagram of a production oven

2. Process Mechanism

- **Loading of Material:** Workpieces or products are placed on trays, conveyors, or trolleys.
- **Heating Phase:** Energy input (Industrial electric or gas combustion) raises chamber temperature. In gas ovens, burners mix air and fuel to produce a stable flame, while in Industrial electric ovens, current passes through resistance elements.
- **Heat Transfer:**

- *Conduction* transfers heat from hot surfaces to material in contact.
- *Convection* circulates hot air or combustion gases to ensure uniform heating.
- *Radiation* from heating elements or flame surfaces contributes to rapid heating.

- **Holding (Soaking) Phase:** Temperature is maintained to achieve uniformity within the material.
- **Cooling/Exhaust Phase:** Controlled cooling or exhaust allows safe handling and prevents product deformation.

3. Comparison of Industrial Electric vs PNG Ovens in Mechanism

- **Industrial electric Ovens:** Simple in design, quiet operation, high precision, but dependent on grid electricity and limited in maximum heating rate.
- **PNG Ovens:** Utilise burner technology, faster heating rates, higher chamber temperatures, and capability for large-scale continuous processing; however, efficiency depends on burner design and heat recovery.

4. Technological Advancements

- Use of **low-NOx burners** and **recuperative/regen burners** for improved efficiency.
- **PLC and IoT-based controls** for real-time monitoring and optimisation.
- **Hybrid systems** (Industrial electric + gas) for flexibility and energy security.

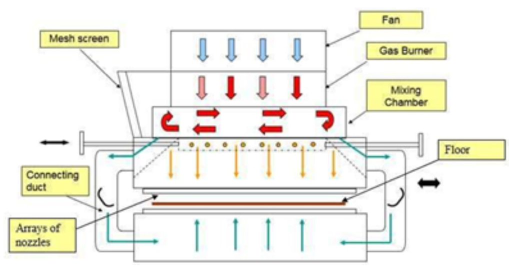


Figure2. Schematic diagram of a production oven

Advantages of Industrial Electric Ovens:

Industrial electric ovens offer several key benefits that enhance productivity, quality, and operational efficiency:

- **High Heat Output with Energy Efficiency:** These ovens can deliver high temperatures efficiently. Modern designs are optimised to maximise heat generation while minimising power consumption, offering a performance advantage over competing systems.
- **Precision Temperature Control:** Equipped with advanced temperature regulation systems, Industrial electric ovens allow precise control over heating processes. Whether through manual knobs or digital interfaces, users can easily adjust settings to match specific process requirements.
- **User-Friendly Operation:** Designed for ease of use, many ovens feature simple control systems that streamline operation and reduce the learning curve. Manufacturers focus on building ovens that are durable, reliable, and easy to maintain, enhancing their value and long-term performance.

Limitations of Industrial Electric Ovens

Despite their advantages, Industrial electric ovens also have some limitations that must be considered:

- **Heat Loss:** At high operating temperatures, heat loss can become significant. This can affect process efficiency and lead to inconsistent results. For thermal processes that require in-chamber cooling, exhaust systems or fans are often necessary to accelerate cooldown cycles and maintain thermal control.
- **Uneven Heating:** Uneven heat distribution may occur if the oven is overloaded or if materials are not properly arranged. This can lead to inconsistent product quality or process inefficiencies. To address this issue, manufacturers often design custom trays or loading systems that ensure optimal spacing and airflow, promoting uniform heat exposure throughout the chamber.

III. Critical Process Parameters Of The Industrial Electric Oven

Controlling the parameters of a curing oven is crucial for producing high-quality products. Understanding how these parameters interact is both a science and an art. The main parameters include:

1. **Air Velocity:** Air velocity refers to the speed of hot air moving inside the curing chamber, usually measured in meters per second (m/s) or feet per minute (ft/min). Uniform airflow distribution across the oven width is essential for even heating and optimal baking results. Higher air velocity speeds up moisture removal, reducing the time needed for complete curing.

2. **Cycle Time:** Cycle time is the average time between the completion of successive units in the manufacturing process and is inversely related to production throughput.

3. Temperature: Temperature is a key factor influencing moisture removal during curing. Experimental studies have shown that moisture content values vary consistently depending on the curing temperature and time, underscoring the importance of precise temperature control for consistent drying and product quality.
4. **Air Flow Rate:** Air flow rate measures the volume of air circulating within the oven. It influences several product attributes, including colour, texture, firmness, and baking duration. Research indicates that moisture content tends to increase with air flow rate up to a certain level, making it an important factor to optimise during the curing process.
5. **Heat Flux:** Heat flux is the amount of energy transferred per unit area per unit time, including contributions from radiation, convection, and conduction. It is typically expressed in $Btu/hr \cdot ft^2$ or W/m^2. Both the total heat flux and the balance of its components affect product quality. While not commonly measured during regular operation, heat flux is critical during oven design and setup.
6. **Humidity:** Humidity inside the curing chamber impacts heat transfer and moisture migration within the product. It affects processes such as starch gelatinisation and enzymatic reactions, as well as the evaporation of moisture from the product surface. Controlling humidity is therefore vital for energy efficiency and product quality.

Here are the critical monitoring parameters for Industrial electric Ovens that significantly impact performance:

1. Temperature Control
   - Accuracy of set vs. actual temperature.
   - Uniformity of temperature distribution across the chamber.
2. Power Consumption
   - Monitoring kWh usage to evaluate efficiency.
   - Identifying energy losses due to insulation or overshooting.
3. Heating Element Performance
   - Resistance and health of heating coils.
   - Response time for heat-up and cooldown cycles.
4. Air Circulation & Heat Transfer
   - Performance of fans/blowers in convection ovens.
   - Air velocity and distribution affecting product quality.
5. Load Capacity Utilisation
   - Effect of batch size on heating performance.
   - Overloading can reduce efficiency and increase cycle time.
6. Process Timing
   - Heating and holding duration.
   - Impact of dwell time on product quality and energy cost.
7. Insulation Integrity
   - Heat losses through oven walls, doors, and seals.
   - Regular monitoring prevents unnecessary energy wastage.
8. Moisture & Humidity Control (if applicable)
   - For baking or curing processes, moisture control ensures consistency.
9. Industrial Electrical Safety Parameters
   - Voltage, current, and phase balance.
   - Protection against overloading and short circuits.
10. Environmental Impact
    - Indirect CO_2 emissions (through Industrial electricity source).

- Energy optimisation helps reduce carbon footprint.

THE TECHNOLOGY AND PROCESS MECHANISM OF PIPED NATURAL GAS (PNG) OVEN

Piped Natural Gas (PNG) ovens represent an advanced fuel-based heating technology widely adopted in Industrial electric applications for baking, drying, curing, and heat treatment processes. They are designed to utilise natural gas supplied through pipelines, ensuring uninterrupted energy flow and efficient combustion. The process mechanism integrates modern burner technology, combustion control systems, and optimised heat transfer methods to deliver high thermal efficiency with reduced environmental impact.

1. Key Technological Components

- **Gas Supply and Regulation:** PNG is delivered via pipeline at regulated pressure using pressure-reducing valves and flow meters. Safety shut-off valves and regulators ensure a stable and secure gas supply.
- **Burner System:** Specially designed **premix or diffusion burners** mix air and natural gas in controlled ratios to ensure complete combustion. Advanced low-NOx burners minimise emissions while maintaining flame stability.
- **Combustion Chamber:** A refractory-lined chamber withstands high temperatures and reduces heat loss. The flame generated by burners heats the chamber walls and circulating gases.
- **Heat Transfer System:**

- *Convection:* Circulating hot gases transfer heat uniformly to the material.
- *Radiation:* Direct radiant heat from the flame and hot surfaces accelerates heating.
- *Conduction:* Occurs when material is in contact with trays or oven surfaces.

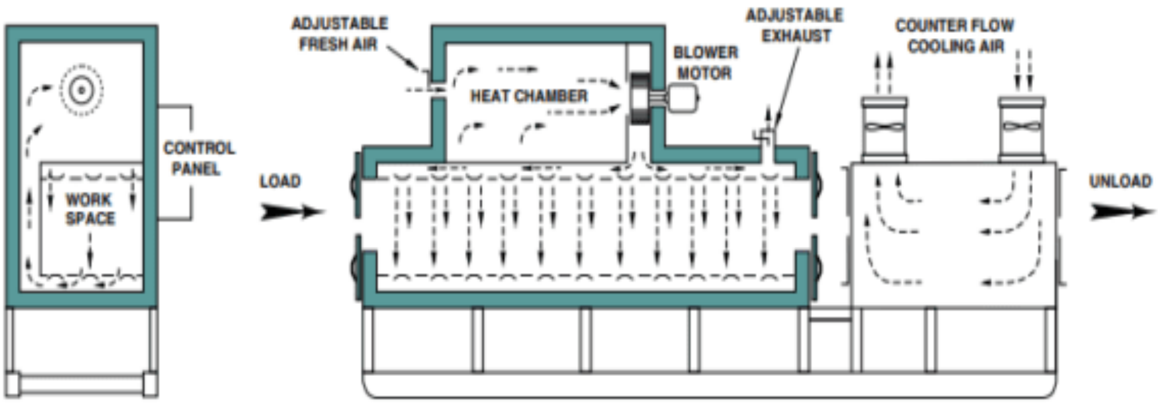
- **Air Circulation and Exhaust:** Forced draft fans circulate hot gases to ensure uniform heating, while exhaust ducts remove flue gases and maintain chamber pressure balance.
- **Control and Automation:** Programmable controllers (PLC/SCADA), thermocouples, and flame sensors regulate gas flow, burner operation, and temperature precision.
- **Safety Systems:** Flame failure devices, pressure sensors, and leak detection ensure safe operation.

2. Process Mechanism of PNG Oven

1. **Gas Intake and Mixing:** PNG enters the burner system where it mixes with combustion air at an optimised air–fuel ratio.
2. **Ignition and Combustion:** The gas-air mixture is ignited (pilot or electronic ignition), producing a stable flame.
3. **Heat Generation:** Combustion releases thermal energy, primarily as hot gases and radiant heat.
4. **Heat Transfer to Product:** The energy is transferred to the material through convection, radiation, and conduction inside the oven chamber.
5. **Temperature Holding:** The oven maintains the required set temperature for the necessary soaking or processing time.

6. **Exhaust and Cooling:** Combustion products and moisture are vented through the flue, while some systems employ heat recovery to improve efficiency.

Circulation Diagram



Full vertical air flow forces heated air down through parts.

3. Advantages of PNG Oven Technology

- Higher heating rates and the ability to reach higher operating temperatures than Industrial electric ovens.
- Continuous, reliable energy supply without fuel storage needs.
- Cleaner combustion compared to coal or oil, with lower CO_2, SOx, and particulate emissions.
- Flexibility to integrate **low-NOx burners** and **heat recovery systems**.
- Lower operating costs in coal-based Industrial electricity grid regions.

4. Limitations

- Efficiency losses due to flue gas exhaust compared to nearly 100% efficient Industrial electric resistance heating.
- Requires pipeline infrastructure, burner installation, and adherence to strict safety codes.
- Potential NOx emissions need to be controlled with an advanced burner design.

OVEN CONVERSION PROCESS: INDUSTRIAL ELECTRIC TO Piped Natural Gas (PNG)

The conversion of an Industrial electric heating to Piped Natural Gas (PNG) involves a systematic process that ensures compatibility, efficiency, and safety. Since Industrial electric ovens utilise resistance heating elements while PNG ovens operate through combustion, the conversion requires significant modification of heating, control, and exhaust systems.

1. Pre-Conversion Assessment

- **Energy Audit:** Evaluate the present energy consumption, operating costs, and carbon footprint of the electric oven.
- **Technical Feasibility:** Assess oven size, temperature requirements, and load patterns to determine suitability for PNG burners.
- **Infrastructure Check:** PNG pipeline connection, supply pressure, and compliance with statutory regulations.

2. Design and Engineering Modifications

- **Removal of Industrial Electric Heating Elements:** Existing resistance coils or infrared heaters are dismantled to make room for the combustion system.
- **Burner Installation:** Suitable PNG burners are installed to provide the required thermal capacity.

- **Combustion Chamber Lining:** Chamber is modified with refractory lining to withstand flame exposure and to reduce heat losses.
- **Air Circulation System:** Forced draft fans and ducts are added or upgraded for proper mixing of combustion gases and uniform heating.
- **Exhaust and Ventilation:** Flue gas ducts, chimneys, and dampers are installed to remove combustion products and maintain chamber balance.

3. Control and Safety Integration

- **Gas Regulation:** Pressure regulators, flow meters, and shut-off valves are installed to ensure a stable, safe gas supply.
- **Automation Controls:** Programmable controllers (PLC/SCADA), thermocouples, and flame sensors are integrated for precise temperature management.
- **Safety Devices:** Flame arrestors, leak detectors, and emergency cut-off systems are mandatory for safe operation.

4. Commissioning and Testing

- **Trial Runs:** Initial ignition and heating trials are performed to check flame stability, burner efficiency, and heat distribution.
- **Performance Validation:** Energy efficiency, heating rate, and product quality are compared with baseline (Industrial electric oven) performance.
- **Emission Monitoring:** CO_2, NOx, and other emissions are measured to validate environmental compliance.

5. Operational Outcomes

- **Energy Cost Reduction:** PNG offers lower operational costs than Industrial electricity in coal-dominated grids.
- **Carbon Emission Reduction:** Conversion typically reduces CO_2 emissions by 40–70% depending on local grid intensity and oven efficiency.
- **Process Efficiency:** Faster heating rates, higher achievable temperatures, and continuous PNG supply.

Advantages of Converting an Industrial Electric Oven to PNG Process

1. Cost Efficiency

- PNG is generally cheaper per unit of heat compared to Industrial electricity.
- Lower operating cost in energy-intensive processes.

2. Continuous Supply

- PNG provides an uninterrupted supply through pipelines.
- No dependency on frequent Industrial electricity outages or diesel backup.

3. Temperature Control & Uniform Heating

- Gas ovens provide faster heating and better control over flame/temperature.
- Suitable for high-temperature applications (metals, ceramics, food industry).

4. Eco-friendliness

- Natural gas burns cleaner than coal, diesel, or furnace oil.
- Reduced CO_2, SOx, and particulate emissions compared to solid/liquid fuels.
- Carbon-intensive grid, switching to PNG can cut process CO_2 by ~40–70%.
- Clean/renewable grid, staying Industrial electric is usually lower-CO_2.

5. Process Efficiency

- Faster start-up and shutdown times compared to Industrial electric resistance heating.
- Better heat transfer for certain Industrial electric processes.

6. Operational Flexibility

- Can be integrated with burners, automatic ignition, and safety controls.
- Easier to adapt for batch as well as continuous processes.

Limitations of Converting an Industrial Electric Oven to a PNG Process

1. High Initial Conversion Cost

- Requires installation of gas pipelines, burners, regulators, and safety systems.
- Existing Industrial electric heating elements must be replaced/modified.

2. Space & Infrastructure Requirement

- Additional piping and ventilation system needed.
- Safety clearance requirements may reduce usable space.

3. Safety Concerns

- Risk of leakage, fire, or explosion if not properly maintained.
- Requires trained operators and regular inspections.

4. Energy Efficiency

- Industrial electric ovens can achieve very high efficiency (near 100%) since Industrial electric energy is directly converted to heat.
- Gas ovens lose some heat through flue gases → lower efficiency.

5. Regulatory Compliance

- PNG usage is subject to safety norms, statutory approvals, and environmental regulations.
- May require local government or utility permissions.

6. Maintenance

- Gas burners and pipelines need periodic maintenance.
- More moving parts compared to Industrial electric resistance elements.

Critical Parameters Monitoring and Control Mechanisms in PNG Ovens

1. Gas Flow Rate & Pressure

- **Impact**: Proper gas pressure ensures stable flame characteristics, uniform heat distribution, and efficient combustion. Fluctuations can cause incomplete combustion, temperature variations, or flameouts.
- **Control Mechanism**:

- Pressure regulators to maintain steady gas pressure.
- Flow meters with alarms for deviations.
- Automated shut-off valves to prevent unsafe conditions.

2. Air-to-Fuel Ratio (Combustion Efficiency)

- **Impact**: A Correct air-fuel mixture is crucial for complete combustion. Too much air leads to energy loss, too little causes CO/NOx emissions and soot formation.
- **Control Mechanism**:

- Oxygen sensors (lambda sensors) in the exhaust to monitor excess oxygen.
- Automated combustion controllers adjust primary/secondary air supply.
- Feedback loop to maintain optimal stoichiometric ratio.

3. Flame Quality & Stability

- **Impact**: Unstable flames can cause uneven heating, safety hazards, and damage to oven lining.
- **Control Mechanism**:

- Flame detectors (UV/IR sensors) to detect flame presence.
- Automatic flame ignition and re-ignition systems.
- Alarms and automatic shut-off if flame failure occurs.

4. Temperature Control & Uniformity

- **Impact**: Uneven or uncontrolled temperatures affect product quality, energy efficiency, and equipment life.
- **Control Mechanism**:
- Thermocouples or RTDs (Resistance Temperature Detectors) placed at multiple oven zones.
- PID (Proportional-Integral-Derivative) controllers for precise temperature regulation.
- Multi-zone heating control for uniformity.

5. Exhaust Gas Composition (Emissions Monitoring)

- **Impact**: High CO, NOx, or unburned hydrocarbons indicate poor combustion and environmental non-compliance.
- **Control Mechanism**:
- Continuous Emission Monitoring Systems (CEMS).
- Exhaust analyser's for O_2, CO, NOx.
- Adjustments in burner settings and air flow to reduce emissions.

6. Moisture & Humidity Control (if applicable for curing/drying ovens)

- **Impact**: High or low humidity affects drying rates, product quality, and energy usage.
- **Control Mechanism**:
- Humidity sensors in the oven chamber.
- Steam injection or dehumidifiers for balance.
- Closed-loop humidity control system.

7. Heat Transfer & Circulation

- **Impact**: Poor circulation causes hot/cold spots, reducing efficiency and consistency in baking, curing, or heating.
- **Control Mechanism**:
- High-temperature fans/blowers for even air distribution.
- Variable Frequency Drives (VFDs) to optimise airflow.
- Regular monitoring of duct integrity and insulation.

8. Insulation Integrity

- **Impact**: Poor insulation increases heat losses, energy cost, and unsafe external surface temperatures.
- **Control Mechanism**:
- Thermal imaging to detect hot spots/leakages.
- Use of refractory linings and ceramic insulation.
- Periodic maintenance and replacement.

9. Safety Parameters

- **Impact**: Prevents accidents like gas leaks, explosions, or overheating.
- **Control Mechanism**:
- Gas leak detectors with automatic shut-off.
- Over-temperature safety cutouts.
- Emergency stop systems.

IV. LITERATURE REVIEW

Specific Analyses from Various Studies on Industrial Electric Ovens

Prof. Kalpana D. Vidhate et al. (2020): This study focuses on a conveyorised oven used for heating lead-acid battery components. The oven, with a total power of 44.625 kW, measures 850 mm in height, 1150 mm in width, and 10,000 mm in length, insulated with 100 mm of Rockwool. It includes an extraction duct that exhausts air at 4800 m³/hr. Steel trays containing 3000 kg of battery components are heated from 40°C to

250°C within 30 minutes. The oven has five working zones, each operating at 7.5 kW with a 10 A current. Zones can be controlled independently according to product requirements. The oven operates smoothly with speed control, the PID temperature controller, the rotary system, and blower speed.

Pieter Verboven et al. (2020): This article presents the use of Computational Fluid Dynamics (CFD) to model 3D isothermal airflow in an Industrial electric forced-convection oven. The fluid flow equations include a fan and turbulence model (k–ε and RNG k–ε), producing comparable results. Validation against hot-film velocity sensor data showed a velocity calculation error averaging 22%, mainly due to turbulence modelling and mesh density limitations. Important factors influencing model accuracy included fan characteristics and oven geometry.

Julio Cesar et al. (2018): An experimentally validated 3D CFD analysis of airflow and thermal processes in a laboratory drying oven with forced air circulation is discussed. Using the conservation of mass, momentum, and k-ε turbulence models, the CFD results closely matched velocity measurements from an Industrial electric oven, with an average calculation error of 18.14%. The study highlights the importance of reliable thermal field prediction for product quality and oven design.

Yuan Yia et al. (2017): This paper addresses the inefficiencies in impingement and continuous flow ovens used in large batch manufacturing lines. Often, ovens become bottlenecks due to suboptimal design. The study develops a CFD model to simulate thermal transfer efficiency in a hot-air convection oven and estimates the maximum conveyor belt speed. The model also evaluates design improvements to reduce cycle times, providing valuable insights for manufacturing optimisation.

F. Pask et al. (2016): Industrial electric ovens consume significant energy in manufacturing. This paper proposes a five-stage systematic approach for oven energy optimisation: defining scope, measuring and analysing variables, understanding the system, planning, and implementation. Applied to a curing oven in a masking tape factory, the method yielded an estimated 29% energy reduction (1,658,000 kWh annually) and 4.7% total plant energy savings, with minimal capital costs. The adaptable approach has broad industry potential.

Frederick Pask et al. (2017): This study presents a novel three-phase method to improve Industrial electric ovens, focusing on energy reduction and process enhancement. The phases include product understanding (using Dynamic Mechanical Analysis and colour tests), process improvement (thermodynamic modelling for temperature uniformity and insulation impact), and process parameter optimisation (temperature, pressure, airflow). Demonstrated on a 1 MW festoon oven, results showed an 87.5% reduction in cooling time, saving 202 hours of annual downtime and cutting gas use by 20–30%.

Y. Bie et al. (2017): Drying is critical in agricultural product processing. Uneven drying in hot-air ovens was investigated using multifunctional drying equipment with air circulation. Tests under loaded and unloaded conditions evaluated temperature uniformity and drying efficiency by modifying tray structure, wind direction, and exhaust moisture control. Results revealed that changing airflow from crossflow to cross-swept flow and controlling exhaust moisture improved drying uniformity and thermal efficiency.

Specific Analyses from Various Studies on Piped Natural Gas (PNG) Ovens

Piped Natural Gas (PNG) ovens have gained significant attention in Industrial electric heating due to their advantages in energy efficiency, environmental impact, and operational cost compared to traditional Industrial electric or fossil-fuel ovens.

Energy Efficiency and Environmental Benefits:
Studies show that PNG combustion produces fewer greenhouse gas emissions, including lower CO_2, sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter, compared to coal-based Industrial electricity or other fossil fuels (IEA, 2020). PNG ovens provide more consistent and controllable heat, improving thermal efficiency in Industrial electric processes such as curing, drying, and baking (Pask et al., 2017). This has

prompted industries to explore the retrofitting of Industrial electric ovens to PNG systems to reduce carbon footprints and energy costs (Vidhate et al., 2020).

Technical Considerations in PNG Oven Design: The design of PNG ovens involves careful integration of burners, heat exchangers, and exhaust systems to optimise combustion efficiency and safety (Verboven et al., 2020). Burner technology has evolved to produce low-NOx emissions while maintaining high thermal output. Proper ducting and airflow management ensure uniform heat distribution, critical for product quality and process consistency (Cesar et al., 2018). Safety systems, including flame detection and gas leak prevention, are essential components in PNG oven operation (Pask et al., 2016).

Industrial Electric Applications: PNG ovens are widely used in sectors such as food processing, pharmaceuticals, automotive, and electronics manufacturing, where precise temperature control and rapid heating are vital (Yia et al., 2017). Their ability to provide continuous, high-temperature environments makes them suitable for curing composites, heat treating metals, and drying products efficiently (Bie et al., 2017).

Challenges and Limitations: Despite their advantages, converting existing Industrial electric ovens to PNG ovens involves upfront investment in gas pipelines, burner installation, and safety upgrades (Vidhate et al., 2020). Space constraints and complex factory layouts can hinder retrofitting efforts. Furthermore, maintaining uniform temperature profiles requires advanced control systems to prevent product defects due to uneven heating (Cesar et al., 2018).

Optimisation and Future Trends: Recent research emphasises the use of computational fluid dynamics (CFD) modelling to optimise airflow and thermal profiles in PNG ovens, improving energy efficiency and reducing cycle times (Verboven et al., 2020; Yia et al., 2017). Integration of PID controllers and automation enhances process control and reduces operational variability (Vidhate et al., 2020). The growing global emphasis on sustainability is likely to drive wider adoption of PNG ovens and innovations in burner technology, emissions reduction, and heat recovery systems.

V. Conclusions: Conversion of Industrial Electric Ovens to Piped Natural Gas (PNG) Systems

This study explores the potential of converting Industrial electric ovens to Piped Natural Gas (PNG)-based systems as a strategy to reduce energy consumption, enhance process efficiency, and minimise environmental impact. Through a review of published literature and analysis of curing process parameters, several key insights and conclusions have emerged:

1. Process Optimisation and Parameter Control

- Multiple optimisation methods have been employed in recent research to improve curing efficiency and product quality. These include both conventional techniques (e.g., Taguchi method) and advanced statistical or algorithmic methods (e.g., Response Surface Methodology, Grey Relational Analysis).
- Parameters such as **oven temperature, air flow rate, pressure, cycle time, and heat flux** significantly influence outcomes like **hardness, moisture content, curing time, humidity levels, and energy usage**.
- The use of tools like **Minitab** and **moisture testing meters** helps in accurately measuring and evaluating these parameters during operation.

2. Energy and Environmental Considerations

- Industrial electric ovens are substantial energy consumers and contributors to greenhouse gas (GHG) emissions.
- Industrial electric ovens, while efficient at the point of use, often rely on Industrial electricity from fossil-fuel-based grids, especially coal, which leads to high **indirect CO_2 emissions**.

- In contrast, **Piped Natural Gas** is a cleaner-burning fossil fuel. It emits approximately **0.20 kg CO_2/kWh**, compared to **0.70–0.90 kg CO_2/kWh** from coal-based Industrial electricity generation.
- **Modern PNG burner systems** achieve thermal efficiencies between **70–85%**, offering the potential to reduce total carbon emissions by **40–70%** in regions reliant on coal power.

3. Operational Advantages of PNG Systems

- PNG-based ovens offer better **temperature control**, **faster heating**, and **improved process stability**, enhancing the quality and consistency of the output.
- Operational costs are reduced due to **lower PNG prices** compared to Industrial electric Industrial electricity tariffs.
- **Continuous pipeline supply** ensures reliability and eliminates the need for fuel storage and manual handling.

4. Implementation and Limitations

- Conversion to PNG requires **capital investment** for installation of gas burners, pipelines, regulators, and enhanced safety systems.
- Strict **safety standards and protocols** must be observed to mitigate fire and gas leak hazards.
- In areas powered by **renewable energy sources**, Industrial electric ovens may remain the more sustainable option in the long term.

5. Strategic Importance of PNG Conversion

- Converting Industrial electric ovens to PNG provides a **transitional pathway** toward cleaner manufacturing practices.
- It offers **immediate and measurable reductions in emissions** while allowing industries time to develop or adopt fully renewable alternatives in the future.

Electric Oven vs. Piped Natural Gas Oven – Environmental Impact

Factor	Electric Oven	Natural Gas Oven	Notes
Energy per use (1 hr)	2 kWh	2.5 kWh equivalent	Gas ovens generally less efficient
Uses per week	4	4	Assumed same usage for comparison
Annual energy use	416 kWh	520 kWh equivalent	Based on 52 weeks
Emission factor	0.5 kg CO_2e/kWh (example grid)	0.19 kg CO_2e/kWh	Electricity varies by region; gas is combustion-based
Annual emissions (CO_2e)	208 kg CO_2e	98.8 kg CO_2e	Lower for gas in fossil-heavy grids
Indoor air quality	No combustion emissions	Emits NOx and other pollutants	Ventilation needed for gas
Efficiency	~85–90%	~60–70%	Electric more efficient in heat transfer
Environmental benefit	Higher if grid is clean	Better only if electricity is fossil-based	Consider local grid mix
Decarbonization potential	Improves over time (cleaner grid)	Fixed (always emits CO_2 when used)	Long-term, electricity is more sustainable

In summary, transitioning from Industrial electric to PNG-based Industrial electric ovens presents a cost-effective and environmentally responsible solution, particularly in regions dependent on carbon-intensive Industrial electricity. This strategy not only aligns with global decarbonization goals but also delivers improved process efficiency and reduced operational costs.

VI. References

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