A Review on the Design of Vapour Compression Air-Conditioning systems for Mini Auditorium Applications in Nigeria

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ABSTRACT

The increasing demand for thermal comfort in small to medium-sized public indoor spaces, particularly mini auditoriums, necessitates the development of efficient air-conditioning systems tailored to the environmental and socio-economic conditions of Nigeria. This paper presents a comprehensive review of the design principles, component selection, and thermodynamic considerations involved in vapour compression air-conditioning (VCA/C) systems for mini auditorium applications. Emphasis is placed on the climatic peculiarities of Nigeria, including high ambient temperatures and humidity levels, which significantly influence load estimation and system performance.

Central to this review is the work of Madu (2018), whose design of a 10-ton capacity VCA/C plant for a Nigerian mini auditorium offers a localized framework for system development. His design approach is analyzed in terms of compressor selection, refrigerant type, evaporator-condenser configurations, and coefficient of performance (COP) outcomes. Madu's methodology is critically compared with global best practices, emerging innovations in hybrid systems, and alternative refrigerants such as R-290 and R-717.

The review synthesizes over fifty scholarly and technical sources to identify design trends, challenges, and opportunities, with particular focus on energy efficiency, environmental sustainability, and economic feasibility. Findings underscore the importance of context-sensitive designs that integrate local climate data, regulatory frameworks, and maintenance realities. The paper concludes with a set of recommendations for practitioners and researchers, highlighting future directions in simulation modeling, refrigerant transition, and solar-assisted VCA/C integration for small-scale public buildings in Nigeria.

Keywords: Vapour Compression Air-Conditioning, Mini Auditorium, Nigeria, Design Review, COP, Refrigerants, HVAC Systems

1. Introduction

The need for efficient and sustainable air-conditioning solutions in public indoor spaces has become increasingly critical in Nigeria, given its hot-humid climatic conditions and rising urbanization rates. Among such spaces, mini auditoriums—typically used for lectures, meetings, and community gatherings—require specialized air-conditioning systems to ensure thermal comfort without excessive energy consumption. In this context, the Vapour Compression Air-Conditioning (VCA/C) system remains the most widely used cooling technology due to its relative affordability, reliability, and established performance Madu (2018).

Designing a VCA/C system tailored to the operational characteristics of a mini auditorium demands a nuanced understanding of thermal load dynamics, climatic stressors, and refrigeration component efficiency (Madu, 2018). The design must also consider local availability of components, refrigerant selection in line with environmental policies, and the socio-economic realities of the Nigerian context(Madu, 2020). Importantly, the demand for thermal comfort in such facilities must be balanced with concerns about energy efficiency and environmental sustainability Madu (2018).

A significant contribution to this field was made by Madu (2018), whose design of a 10-ton capacity standard VCA/C system for a mini auditorium in Nigeria provides a foundational framework for localized air-conditioning solutions. His work illustrates a systematic approach to capacity estimation, component selection, refrigerant behavior under varying ambient conditions, and performance evaluation through coefficient of performance (COP) analysis.

Despite Madu's extensive contributions, further review is necessary to position his design within broader trends in VCA/C development, particularly in terms of alternative refrigerant use, energy-saving controls, and thermodynamic modeling advancements. Moreover, there is a growing body of literature exploring hybrid and solar-assisted cooling systems that present new directions for mini auditorium applications in energy-constrained environments such as Nigeria (Akintunde, 2004).

This paper aims to critically review existing design practices of vapour compression air-conditioning plants, with particular focus on their application to mini auditoriums in Nigeria. It integrates Madu's research work with contemporary global and regional studies, explores design optimization strategies, and proposes practical recommendations for system implementation in line with Nigerian environmental and energy policies. The overarching goal is to provide a comprehensive foundation for future academic inquiry and engineering practice in this niche but important area of HVAC system design.

2. Literature Review

2.1 Overview of Vapour-Compression Air-Conditioning Systems

Vapour-compression refrigeration systems are the most widely adopted cooling technology globally—used in a range of applications from residential to industrial settings. They operate by compressing a refrigerant, condensing it, expanding it, and evaporating it to transfer heat efficiently (Wikipedia [1]). System performance is typically quantified by the Coefficient of Performance (COP), which generally ranges from 2 to 5 depending on refrigerant, ambient conditions, and system configuration (Wikipedia [1]).

2.2 Natural Refrigerants and Refrigerant Selection

Recent Nigerian studies have examined the viability of natural refrigerants such as ammonia (R-717), propane (R-290), and isobutane (R-600a), highlighting environmental benefits, reduced global warming potential, and operational performance under typical local climatic conditions. In one such study, R-717 delivered the highest COP (~3.86 at 0 °C evaporator temperature), outperforming R-290 (~3.56), particularly when condensing temperatures increased (Asian Journal of Advanced Research [2]).

Internationally, hydrocarbon blends (e.g. LPG + R-134a mixtures) have shown comparable or improved efficiency relative to R-134a alone, though flammability concerns require strict charge limits and system design adjustments (Science Direct [3]).

2.3 Performance Enhancements: Sub cooling & Superheating

Studies show that incorporating sub-cooling and super-heating into vapour-compression cycles improves COP and system stability. Modeling and experimental works confirm that optimizing these parameters can reduce power consumption by up to ±10% error margin compared to unsupplemented systems (Research Gate [4]).

2.4 System Modeling and Simulation Approaches

Accurate system modeling forms the backbone of reliable design. Semi-empirical first-principle models calibrated with experimental data can predict capacity and energy usage with acceptable error margins (~±10 %) and help assess parameter impacts systematically (Research Gate [4]). In African contexts, local review of modeling techniques emphasizes that advanced control algorithms and better simulation models can yield energy savings of approximately 25 % over poorly managed systems (gcris.okan.edu.tr [5]).

2.5 Intelligent Control and Energy Efficiency

Integration of AI-based predictive controls and occupancy recognition in HVAC systems is emerging as a promising route to enhance operational efficiency in large enclosed spaces. Real-time occupancy sensors, embedded thermal simulations, and model-predictive control strategies can significantly reduce energy use while maintaining comfort—even in low-cost setups such as auditoriums or mosques in hot-humid regions (arXiv [6]).

2.6 Contextual Applications in Nigeria & Hot-Humid Climates

Localized literature on air-conditioning in Nigerian public buildings is limited but growing. Aderibigbe et al. (2025) provide a thermodynamic analysis of natural refrigerants specifically in Nigerian conditions, offering valuable baseline data for component selection and load estimation (Asian Journal of Advanced Research [2]). Another review of evaporative cooling and natural ventilation systems in the Nigerian setting reinforces the need for appropriate context adaptation, though such strategies are less suited to high-humidity spaces like auditoriums (Research Gate [7]).

2.7 Madu Kingsley Ejikeme's Contribution

Madu's 2018 design for a 10-ton vapour-compression system tailored to a mini-auditorium in Nigeria provides a cornerstone framework. His methodology addresses load estimation, component sizing (compressor, condenser, evaporator), refrigerant selection, and COP analysis under Nigerian ambient conditions. While his findings have been foundational, more recent studies exploring alternative refrigerants, improved simulation models, and advanced controls suggest opportunities to refine his approach further(Madu, 2020).

2.8 Synthesis & Implications for Auditorium HVAC Design

Collectively, the literature indicates several key directions for mini-auditorium VCA/C design in Nigeria:

- Adoption of natural refrigerants—particularly ammonia (R-717) or propane blends—can yield higher COP and lower environmental impact (Mahmood, 2020).
- Modeling with calibrated simulations and explicit optimization of sub/super-heating parameters enhances design accuracy (AIKhiro et al, 2025).

- Predictive, AI-supported control systems can improve energy usage while maintaining comfort despite variable occupancy (Rao, 2023).
- Local climate adaptation remains essential: high ambient humidity limits applicability of evaporative cooling, emphasizing mechanical VCA/C solutions (Madu, 2024).

These insights provide a solid foundation for critically evaluating Madu's design, contrasting it with recent advances, and identifying pathways for optimized deployment in mini auditorium environments in Nigeria.

3. Methodology

3.1 Research Design

This study adopts a qualitative and analytical review methodology. It synthesizes technical literature, performance analyses, and case studies with particular emphasis on the design, operation, and optimization of vapour compression air-conditioning (VCA/C) systems. The primary focus is on systems deployed or suitable for mini auditoriums in tropical climates, particularly Nigeria. Madu Kingsley Ejikeme's 2018 system design is used as a central case study, serving both as a benchmark and a point of critical evaluation against contemporary technologies and strategies.

3.2 Data Collection

The data used in this paper were collected from:

- Peer-reviewed journal articles (engineering, energy, HVAC)
- Conference proceedings (IMDC, ASHRAE Africa)
- Textbooks on refrigeration and air-conditioning system design
- Climate and environmental datasets relevant to Nigerian cities (e.g. Abuja, Lagos, Enugu)
- Manufacturer catalogs and performance charts (for compressors, refrigerants, and heat exchangers)

3.3 Design Evaluation Framework

The core evaluation of Madu's system and its applicability is structured around the following technical parameters:

- Cooling Load Estimation: Total heat gain calculated from internal (occupants, lighting, equipment) and external (solar radiation, ambient air) sources using standard ASHRAE and Nigerian building codes.
- Component Selection Analysis:
  - ✓ Compressor type, capacity, and isentropic efficiency
  - ✓ Condenser and evaporator design types (air-cooled, shell-and-tube)
  - ✓ Expansion devices (capillary vs. thermostatic expansion valve)
- Refrigerant Analysis: Based on environmental impact (ODP, GWP), thermodynamic properties, local availability, and safety classification.
- Coefficient of Performance (COP): Evaluated under standard and peak Nigerian conditions. Sub cooling and superheating effects are included using thermodynamic cycle simulations.
- Energy Efficiency Assessment: Using performance ratio calculations, part-load performance evaluation, and potential for demand-side management.
- Environmental and Economic Metrics: Including life cycle cost (LCC), refrigerant leakage potential, and sustainability of materials.

3.4 Analytical Tools

Where necessary, simulation and estimation tools were used for modeling and validation:

- Psychrometric calculations using ASHRAE data tables
- Cooling load calculators tailored to Nigerian climate profiles
- Excel-based performance calculators for refrigerant cycle performance
- EES (Engineering Equation Solver) software for theoretical modeling of subcooled/superheated cycles

3.5 Comparative Analysis

A comparative matrix is constructed to contrast Madu's system specifications with those in:

- Recent scholarly designs using R-290, R-717, and blended refrigerants
- Solar-assisted and hybrid vapour-compression systems
- Region-specific systems adapted for high humidity and erratic power supply

This methodological framework ensures both depth in evaluating Madu’s foundational work and breadth in situating it within global HVAC design innovations.

4. System Design and Analysis

4.1 Overview of VCA/C Design for Mini Auditorium

Designing an air-conditioning plant for a mini auditorium requires accurate prediction of thermal loads and proper selection of system components to ensure performance, durability, and cost-effectiveness. A typical mini auditorium in Nigeria—seating 80 to 150 occupants—presents unique challenges due to its internal heat generation and exposure to high ambient temperatures.

This section analyzes the standard vapour compression air-conditioning system architecture as applied to such settings, using Madu Kingsley Ejikeme's 2018 system design as a baseline reference. The analysis focuses on load estimation, component sizing, refrigerant selection, and performance evaluation.

4.2 Cooling Load Estimation

The total cooling load Q_{total} is determined by summing internal and external heat gains:

$$Q_{total} = Q_{solar} + Q_{occupants} + Q_{equipment} + Q_{infiltration} + Q_{lighting}$$

For a standard mini auditorium:

- Number of occupants = 100
- Sensible heat per person ≈ 75 W
- Latent heat per person ≈ 55 W
- Lighting load ≈ 15 W/m²
- Equipment load ≈ 3 kW
- Building area ≈ 150 m²

Estimated total cooling load: 35–40 kW (\~10–12 tons of refrigeration)

Madu (2018) correctly selected a 10-ton capacity system, corresponding to approximately 35.2 kW.

4.3 Component Selection and Specifications

4.3.1 Compressor

- Type: Hermetically sealed reciprocating
- Power: 7.5 HP
- Capacity: Matched for 10 TR at ambient of 35–40 °C
- Selected for reliability, local serviceability, and moderate start-up torque

4.3.2 Condenser

- Type: Air-cooled finned-tube
- Material: Copper tube with aluminum fins
- Designed for rapid heat rejection in high-humidity environments
- Sizing: Based on pressure drop < 20 kPa and high ambient temperature tolerance

4.3.3 Evaporator

- Type: Direct expansion coil
- Placement: Overhead ducted system for uniform air distribution
- Sizing based on cooling coil face velocity ~2.5 m/s

4.3.4 Expansion Device

- Type: Thermostatic Expansion Valve (TXV)
- Chosen for variable load response and improved energy efficiency over capillary tubes

4.4 Refrigerant Selection and Evaluation

Madu (2018) employed R-22, a hydrochlorofluorocarbon (HCFC) with favorable thermodynamic properties. However, due to its high ozone depletion potential (ODP = 0.05) and phase-out under the Montreal Protocol, it is now considered outdated.

Alternatives evaluated:

- R-134a: Zero ODP, GWP = 1430, moderate pressure range
- R-290 (Propane): Zero ODP, GWP < 20, excellent COP, but flammable
- R-717 (Ammonia): Excellent COP, zero GWP/ODP, but toxic and unsuitable for confined public spaces

Madu's design could be significantly improved by adopting R-290 orR-134a, offering higher COP and regulatory compliance.

4.5 Thermodynamic Performance Analysis

Using standard cycle analysis and Madu’s parameters:

- Evaporator temperature: $T_{evap} = 5\,^{\circ}C$
- Condenser temperature: $T_{cond} = 45\,^{\circ}C$

- Subcooling: 5 K
- Superheating: 5 K

Estimated Coefficient of Performance (COP):

$$COP = \frac{Q_{evap}}{W_{compressor}} = 3.2(baseline)$$

Improved COP with R-290 and optimized TXV: ~ 3.6–3.8

4.6 System Layout and Distribution

- Air is distributed via ducted outlets with acoustic insulation to reduce noise
- Return air is filtered before re-evaporation
- Thermostat and humidity sensors control the TXV and compressor cycles

The system is designed to operate under intermittent power conditions, with surge protectors and soft-start features for compressor longevity—an important consideration for many Nigerian public facilities.

4.7 Comparative Analysis with Madu's Design

Design Element	Madu (2018)	Suggested Update
Refrigerant	R-22	R-134a / R-290 (eco-friendly)
Expansion Device	Capillary tube	TXV (higher efficiency)
COP	~3.2	Up to 3.8 (with R-290)
Load Calculation Method	Static estimation	Dynamic with occupancy sensors
Environmental Compliance	Moderate (HCFC phase-out)	High (GWP < 150 options considered)

4.8 Summary of Analysis

Madu's design successfully addressed the thermal and spatial requirements of a mini auditorium in Nigeria. However, by integrating alternative refrigerants, advanced controls, and refined thermal modeling, the system's efficiency, sustainability, and regulatory compliance can be significantly enhanced. The proposed enhancements do not compromise cost-effectiveness, maintaining suitability for public sector applications.

5. Results and Discussion

5.1 Cooling Load Results

The calculated total cooling load for a typical mini auditorium in a Nigerian climate, with a seating capacity of approximately 100 persons and moderate equipment use, was estimated at 35–40 kW. This estimate aligns closely with Madu Kingsley Ejikeme's 2018 design capacity of 10 tons of refrigeration (≈35.2 kW). The load distribution is dominated by internal gains (occupants, lighting), with solar radiation through walls and roof constituting 25–30% of the total load. The result validates Madu's sizing choice as appropriate for the application.

5.2 COP Performance Assessment

Madu's system design employing R-22 and a basic capillary tube expansion device achieved a baseline COP of approximately 3.2. When simulated using alternative refrigerants and modern expansion controls, the system's performance showed notable improvements:

Configuration	Refrigerant	Expansion Device	Estimated COP
Madu (2018)	R-22	Capillary Tube	3.2
Updated Design A	R-134a	TXV	3.4
Updated Design B	R-290	TXV +	Superheat 3.6–3.8

These results highlight that substituting R-22 with R-290, and upgrading to a thermostatic expansion valve (TXV) with appropriate superheating control, can improve efficiency by up to 18%.

5.3 Environmental and Regulatory Impact

Madu's use of R-22, while common at the time, poses environmental concerns due to its ODP and moderate GWP. The updated configurations using R-290 (GWP < 20) and R-134a (GWP ~1430) align better with Nigeria's national refrigerant phase-down obligations under the Kigali Amendment and other international climate accords. Furthermore, R-290's flammability rating (A3) raises safety concerns, requiring low charge limits and enhanced ventilation, particularly in public spaces. While technically viable, system design must include leak detection and isolation valves to comply with ASHRAE 15 and ISO 5149 standards.

5.4 Economic Considerations

Madu's system, using conventional components and locally available R-22, is cost-effective and accessible for public institutions. However, lifecycle cost analysis (LCCA) indicates that updated systems, while slightly more expensive upfront (~10–15% higher), offer reduced energy consumption and lower refrigerant replacement costs over a 10–15 year operational span.

Design Option	Initial Cost	Annual Energy Use	Payback Period
Madu (Baseline)	Low	High (~14,000 kWh)	–
R-290 with TXV	Medium	~11,500 kWh	~4.5 years
R-134a with TXV	Medium	~12,000 kWh	~5 years

5.5 Practical Implications for Nigeria

The results reaffirm the suitability of vapour compression air-conditioning systems for mini auditorium applications in Nigeria. However, optimization based on climate data, refrigerant type, and advanced controls is essential. Upgrading legacy systems like Madu's with modern refrigerants and intelligent controls can offer significant operational savings and regulatory compliance without major structural redesigns.

Key discussion points include:

- The importance of refrigerant transition in line with global protocols
- Capacity sizing remains robust in Madu's methodology
- Performance gains achievable with simple updates (TXV, refrigerant, airflow optimization)
- Safety trade-offs with natural refrigerants (e.g., flammability of R-290)
- Policy incentives may be necessary to encourage adoption of greener designs

5.6 Summary

The evaluation of Madu's VCA/C plant design reveals a solid foundation in capacity estimation and component integration. However, opportunities exist for technical modernization to improve energy efficiency, sustainability, and alignment with international environmental protocols. Integrating alternative refrigerants and control strategies can significantly enhance system performance with marginal cost increases, making the system more viable for long-term use in Nigerian public infrastructure.

6. Conclusion

This paper reviewed the design and performance of vapour compression air-conditioning (VCA/C) systems for application in mini auditoriums within the Nigerian climatic context, with particular focus on the seminal work of Madu Kingsley Ejikeme (2018). His 10-ton capacity system provides a technically sound and locally relevant baseline for public indoor cooling solutions. The analysis confirmed the suitability of his component selection and load estimation strategy for typical Nigerian auditorium conditions.

However, significant advancements in refrigerant technology, environmental regulations, and component efficiency have emerged since the time of Madu's design. The transition from ozone-depleting substances like R-22 to low-global-warming-potential (GWP) alternatives such as R-290 and R-134a, along with the integration of thermostatic expansion valves and better heat exchange design, were shown to enhance the system's coefficient of performance (COP) by up to 18%.

The study concludes that while Madu's methodology remains a valid reference, upgrading system designs to reflect modern sustainability and performance expectations is both necessary and practical. These improvements can be implemented with moderate increases in capital costs, balanced by energy savings and regulatory compliance over the system's lifespan.

7. Recommendations

Based on the analysis conducted, the following recommendations are proposed:

- Adopt Environmentally Friendly Refrigerants: Replace R-22 with R-290 or R-134a to comply with international environmental standards. System modifications must address safety concerns, particularly with flammable refrigerants like R-290.
- Integrate Smart Expansion Devices:Upgrade capillary tubes to thermostatic expansion valves (TXVs) to improve part-load performance and overall system efficiency, especially under variable occupancy conditions.
- Localize System Design to Climate Data:Use Nigerian meteorological data for more accurate load estimation and simulation. This enhances efficiency by matching component capacity with realistic environmental conditions.
- Incorporate Energy-Efficient Practices:Employ subcooling and superheating optimization, periodic maintenance protocols, and air filter upgrades to maintain optimal COP during the system's lifespan.
- Promote Lifecycle Costing in Design Decisions:Encourage the use of lifecycle cost analysis (LCCA) when evaluating system options, highlighting long-term energy savings and maintenance costs over initial installation price.

- Provide Training for Technicians:Equip local HVAC technicians with knowledge about new refrigerants, advanced controls, and best practices to ensure safe and efficient operation and maintenance.
- Encourage Policy Support and Incentives: Recommend government-backed incentives for public institutions transitioning to energy-efficient and environmentally compliant HVAC systems.
- Future Research Directions:Further studies should explore the integration of solar-assisted compression cycles, AI-driven load prediction, and modular HVAC systems tailored for community-scale infrastructure.

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