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Article

Implementation of a solar-thermal hybrid air conditioning system in Muscat for energy conservation

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Abstract: The need for global energy conservation has become more urgent because of the negative effects of excessive energy use, such as higher fuel consumption, greater environmental pollution, and depletion of the ozone layer. There has been a significant increase in the demand for central and high-capacity household air conditioning systems in Muscat in recent years. The need for this is influenced by factors such as arid climate, increasing temperatures, air pollution, and population increase. As a result, there has been a significant increase in electricity use, putting a strain on power resources. To tackle this difficulty, the incorporation of solar collectors as supplementary thermal compressors in air conditioning systems offers a chance to utilise renewable energy sources. The objective of this hybrid technique is to enhance the effectiveness of cooling systems, hence minimising the need for electricity, and lowering the release of environmental pollutants.

Keywords: solar energy; energy conservation; radiation; hybrid air conditioning; thermal energy

1. Introduction

The increasing need for air conditioning in Muscat is a result of the climate and fast urbanisation issues faced in the region. Elevated temperatures and atmospheric pollution require widespread reliance on air conditioning, resulting in heightened energy usage. This research suggests using solar-thermal technology into air conditioning systems as a solution to address these difficulties and improve energy efficiency. Muscat has consistently high temperatures throughout most of the year, resulting in a significant need for cooling and thus, a huge need for energy [1]. Elevated temperatures and atmospheric pollution need the greater utilisation of air conditioning systems, resulting in heightened energy usage. Conventional air conditioning systems that rely only on electricity from the power grid make a substantial contribution to energy consumption and the resulting environmental effects.

Air conditioning (AC) is the process of regulating air properties, such as temperature, humidity, cleanliness, and distribution technique, to meet certain requirements [2]. Air conditioning, also referred to as the cooling of air, involves the removal of heat, which is usually accomplished using electricity. The installation of a solar energy system becomes appealing due to the rise in electricity consumption [3]. The renewable nature of solar energy makes it highly suitable for utilisation in sub-tropical nations. To tackle these difficulties, the suggested system combines solar collectors with air conditioning units to utilise renewable energy for the purpose of cooling. Solar collectors capture thermal energy to enhance the compression process of the system. This strategy enhances cooling efficiency and minimises dependence on traditional electricity. The system, which provides comprehensive control over capacity, mechanism, ease of implementation, high reliability, silent operation, long lifespan, and low maintenance costs, is an excellent choice for using solar energy efficiently and cost-effectively in cooling applications [4].

The main objective of this project is to enhance and optimise the conventional air conditioning unit to function alongside solar energy as an auxiliary system, with the purpose of decreasing energy usage, environmental contamination, and noise levels [5]. Deploying a solar-thermal hybrid system provides numerous advantages:

- Energy conservation: Decreases electricity usage, alleviating pressure on power infrastructure.
- Environmental impacts: Reduces emissions linked to traditional cooling systems.
- Resource efficiency: Harnesses sustainable energy sources, diminishing dependence on non-renewable fossil resources.

Implementing solar-thermal technology in the air conditioning system in Muscat is a practical approach to saving energy and reducing the negative environmental effects caused by high cooling requirements. This strategy is in line with worldwide initiatives promoting sustainable energy practices and tackles the specific issues of energy use in fast growing urban regions [6]. The system’s performance is evaluated by analysing its operational viewpoint and commercial applications.

2. Background

Muscat endures extended periods of elevated temperatures year-round, leading to a significant increase in the need for electricity to power cooling systems. The use of conventional air conditioning systems worsens energy usage and adds to environmental consequences, such as heightened carbon emissions [7]. It is crucial to implement sustainable cooling solutions, especially in residential buildings, to address these difficulties and encourage energy conservation.

2.1. Hybrid solar-thermal air conditioning system for Muscat

The solar-thermal hybrid air conditioning system combines solar thermal technology with traditional air conditioning systems to enhance cooling efficiency and decrease reliance on grid electricity [8]. This technology provides numerous benefits in Muscat’s residential buildings:

Energy conservation is achieved by utilising solar energy for cooling, which reduces the need for traditional electricity. This helps to relieve pressure on the power infrastructure and decreases operational expenses for households.

The utilisation of renewable solar energy reduces carbon emissions linked to cooling operations, so supporting Muscat’s sustainability objectives.

The system is specifically engineered to endure the climatic conditions of Muscat, guaranteeing dependable and effective operation even in extreme temperatures.

2.2. Application in residential buildings

To effectively deploy the solar-thermal hybrid AC system in residential buildings in Muscat, it is essential to evaluate the following factors [9]:

Roof space utilisation: Solar collectors can be placed on rooftops to maximise access to sunlight and enhance energy production.

System integration: The hybrid system must smoothly and effectively combine with the current air conditioning infrastructure, reducing the need for extensive modifications, and minimising any inconvenience to inhabitants.

User education and engagement: It is essential to educate inhabitants about the advantages and functioning of the hybrid system to ensure its effective adoption and long-term sustainability.

3. Methodology

The approach employed in this study strictly follows established research protocols as mentioned in the study of Li et al. [10]. The primary objective is to design and refine a solar-thermal hybrid AC system that is specifically tailored for implementation in Muscat. The research process is outlined below:

a) Aggregation of meteorological data

Goal: Collect crucial meteorological information to guide the development of the system.

Data pertaining to the weather conditions in Muscat was gathered. A meteorological year was created by analysing solar radiation parameters on an hourly, monthly, and annual basis.

b) Calculation of cooling load

Goal: Calculate the necessary capacity of the cooling system.

Procedure: The calculation of the cooling load was performed to determine the necessary amount of cooling, which is crucial for accurately determining the system size.

c) System design and dimensioning

Goal: Develop and determine the specifications of the various components of the AC system.

The size and specifications for the system components were derived based on the collected meteorological data and established design criteria.

d) System optimization

Objective: Improve system efficiency to reduce energy expenses.

Methodology: The suggested system was enhanced to achieve maximum energy efficiency by utilising simulations to fine-tune component settings and system configurations for optimal performance.

e) Acquisition and construction

Objective: Obtain materials and build the experimental prototype.

Procedure: After optimising the system, the required components were acquired. Subsequently, the system was constructed and deployed to undergo testing.

f) System testing and life cycle assessment

Objective: Assess the performance and economic feasibility of the system.

Procedure: The assembled system underwent thorough testing. Life cycle costs were determined by evaluating the system's price competitiveness and thermal efficiency for residential applications.

g) Recommendations and analysis

Goal: Examine findings and suggest improvements.

Analysis: The data were examined to pinpoint areas where technology advancements and efficiency enhancements may be made.

Figure 1 illustrates the complete setup of the proposed hybrid solar-thermal air conditioning system, highlighting the integration of solar collectors with conventional cooling components [11]. Recommendations were made to enhance both the economic and technical performance of the system. Additionally, strategies for advancing research and development in solar cooling technologies were explored.

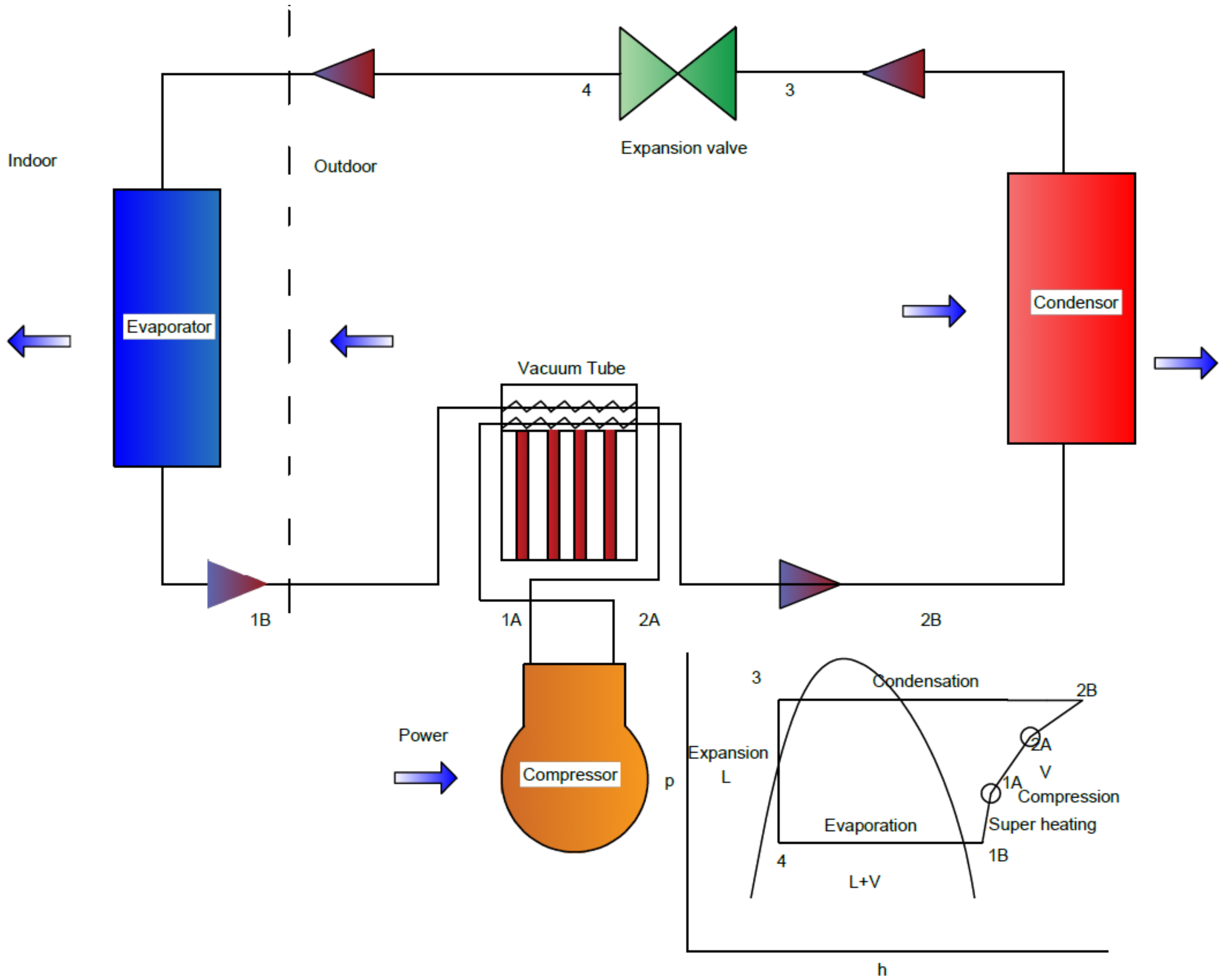

Figure 1. Proposed schematic diagram for hybrid solar-thermal air conditioner.

4. System design and description

The suggested system incorporates a direct current (DC) air conditioner with a vacuum tube solar collector, as depicted in **Figure 1**. The objective of this system is to achieve the same level of efficiency as conventional AC systems by harnessing renewable energy sources. Every element within the system is assessed separately to guarantee the best possible performance and compatibility [12]. The system is engineered to function reliably in different circumstances, aiming to achieve cooling efficiency that is on par with traditional air conditioning equipment.

4.1. Calculation of refrigeration load

Refrigeration load is the quantity of thermal energy that needs to be removed from a given area to reach and sustain a desired temperature. Thermal energy naturally transfers from regions with higher temperatures to regions with lower temperatures. In the realm of air conditioning, this process entails the movement of heat from the interior of a structure to the external surroundings [13].

The refrigeration load entails determining the rate at which thermal energy needs to be extracted from an indoor space. Thermal transfer occurring through walls, windows, and doors as a result of variations in temperature between the inside and outside environments [14]. The cooling demands of a location are affected by variables such as the size of the area and the composition of the building components. Furthermore, the presence of humans in the area results in the generation of heat due to metabolic processes. The metabolic heat output fluctuates considerably depending on the specific activities performed in the room, such as sleeping or dancing. In addition, electronic gadgets, and other appliances, such as printers and laptops, produce extra heat that needs to be considered when calculating the overall cooling requirement.

By precisely evaluating these elements, the system can be customised to effectively extract the necessary quantity of heat from the indoor environment, ensuring comfort while maximising energy efficiency.

4.2. The air conditioning system

Figure 2. Compressor in air conditioning system.

Both building and vehicle air conditioning systems rely on five crucial components: the compressor, refrigerant, expansion device, evaporator, and condenser [15]. Each component is detailed in depth below, accompanied by diagrams that demonstrate their roles within the system. **Figure 2** depicts the compressor, which plays a vital role as the central component of the AC system, responsible for circulating refrigerant throughout the entire system.

The process involves compressing the refrigerant vapour, which results in an increase in both its pressure and temperature. This allows for easier circulation of the refrigerant throughout the system. The compressor is usually operated by electricity and plays a crucial role in sustaining the refrigeration process. A refrigerant is a chemical substance that functions as a coolant by collecting heat from the surrounding environment and circulating within the circuits of an air conditioning system [16]. The expansion device is located between the condenser and evaporator and is responsible for controlling the flow of refrigerant. It regulates the conversion of the refrigerant from a high-pressure (HP) liquid to a low-pressure (LP) liquid, which initiates the cooling process in the evaporator [17].

Figure 3 depicts the expansion device employed in an AC system. During the process of refrigerant circulation, the evaporator uses the refrigerant in its liquid condition to absorb heat from the cooling space and transfer it into the system [18].

Figure 3. Expansion device in air conditioning system.

Evaporator, situated in the indoor unit of the air conditioning system, has a crucial function in regulating the indoor air, as depicted in **Figure 4**. The process involves the absorption of heat from the indoor air into the liquid refrigerant, which leads to the evaporation of the refrigerant and efficiently cools the surrounding space [19].

Figure 4. Evaporator in air conditioning system.

The condenser, located adjacent to the compressor in the outside unit (as shown in **Figure 5**), is responsible for releasing the absorbed heat to the surrounding environment. The function of this process is to lower the temperature and pressure of the vapour refrigerant produced by the compressor, causing it to condense into a liquid state again [20].

Figure 5. Condenser in air conditioning system.

The combination of these components creates a seamless cycle that is crucial for the air conditioning system to effectively extract heat from the inside of a building or vehicle and expel it outside, resulting in efficient cooling of the indoor area [21].

4.3. Vacuum tube collector (VTC) system

The VTC system utilises cutting-edge solar technology, incorporating a sequence of evacuated tubes engineered to optimise the absorption and conversion of solar radiation into amount of heat energy. These systems are mostly used in active solar heating applications, specifically for water heating in residential and commercial settings.

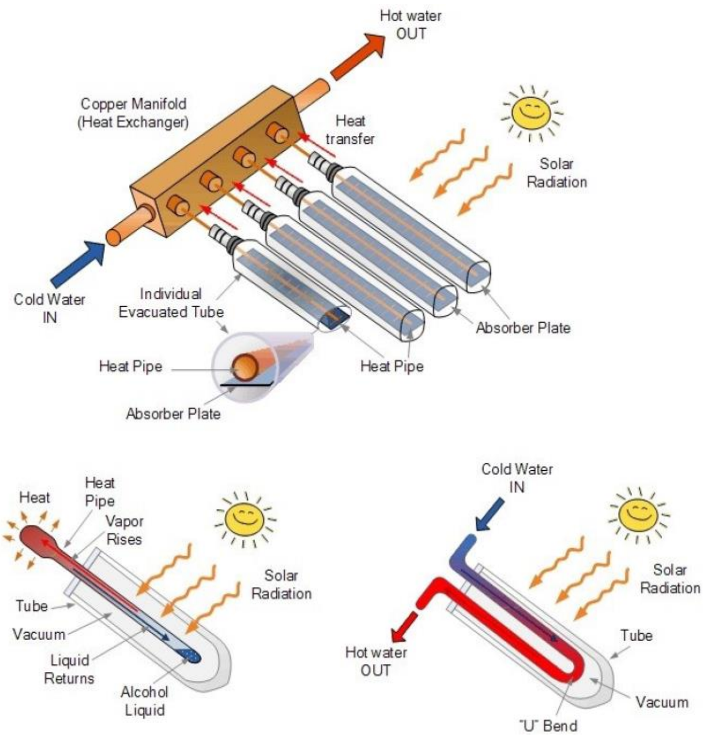

Figure 6. Vacuum tube collector solar system.

Usually installed on rooftops, these collectors are designed to endure various weather conditions, guaranteeing robustness and longevity. Their design and construction are vital for uninterrupted operation under different climatic conditions. The vacuum tube collector system (**Figure 6**) consists of individual tubes made of durable, airtight glass that encloses an inner metal tube called the absorber tube. This configuration reduces thermal loss by creating a vacuum between the two tubes, hence improving the efficiency of the device in capturing solar radiation.

The heat pipe, a crucial element, efficiently conducts the absorbed heat upwards into the inner metal tube. The heat pipe functions within defined pressure parameters, as specified in references [22], generating a dynamic setting in which the lower end of the pipe reaches the boiling point, while the higher end undergoes condensation. This mechanism leads to an effective heat transfer driven by a phase transition from the "hot" end to the "cold" end of the pipe.

The evacuated tube design enables efficient solar energy collecting while minimising heat loss to the surroundings. At the high temperature region, the liquid contained within the heat pipe undergoes boiling, effectively absorbing thermal energy from the sun. The vapour produced moves upwards to the colder part, where it undergoes condensation, transferring the heat to the water or another heated fluid. The process of boiling and condensing in the vacuum tube system effectively transfers thermal energy, making it very efficient for solar thermal applications. Vacuum tube collector systems utilise advanced technology to harness the sun's energy, making them a dependable and sustainable method for heating water. These systems make a substantial contribution to energy conservation initiatives [23].

5. Functioning of the system

The presented technology utilises solar energy in conjunction with conventional vapor-compression refrigeration methods to operate the air conditioning system. This hybrid strategy not only improves energy efficiency but also harnesses renewable energy sources to minimise the overall environmental footprint.

The system initiates with the solar unloading unit, which efficiently catches solar radiation and turns it into thermal energy. Water serves as the thermal transfer medium, enabling this conversion. The hot water is stored in a thermal reservoir, guaranteeing a continuous supply of thermal energy for the system's functioning.

The central component of the system is a traditional direct expansion, mechanical, vapor-compression refrigeration system. Its main purpose is to provide air cooling by extracting heat from internal areas and releasing it outside [24].

Evaporation begins at the evaporator coil, which is situated inside the cooling area. In this process, a frigid, low-pressure refrigerant assimilates thermal energy and undergoes vaporisation, transitioning from a liquid to a gaseous phase. This process of phase transition extracts thermal energy from the indoor air, resulting in its efficient cooling.

Compression: The gaseous refrigerant is then sent to the compressor, where it is pressurised to a high level, causing its temperature to increase dramatically.

Condensation: The hot, high-pressure gas is sent to the condenser coil, where it dissipates its heat to the surrounding air. As the refrigerant releases thermal energy, it undergoes condensation and returns to a liquid state.

Expansion: The heated liquid flows via an expansion device, where its temperature and pressure are decreased, to be ready to re-enter the evaporator and resume the cycle.

The schematic depicted in **Figure 7** showcases the cyclical operation of the refrigeration system, emphasising the integration of hybrid solar thermal energy to optimise the efficiency of the cooling process. By using solar energy to aid in heating the refrigerant, the technology decreases the energy requirement of the compressor, therefore saving electricity and reducing operational expenses. This integration enhances system efficiency and promotes sustainable energy practices by decreasing reliance on non-renewable energy sources.

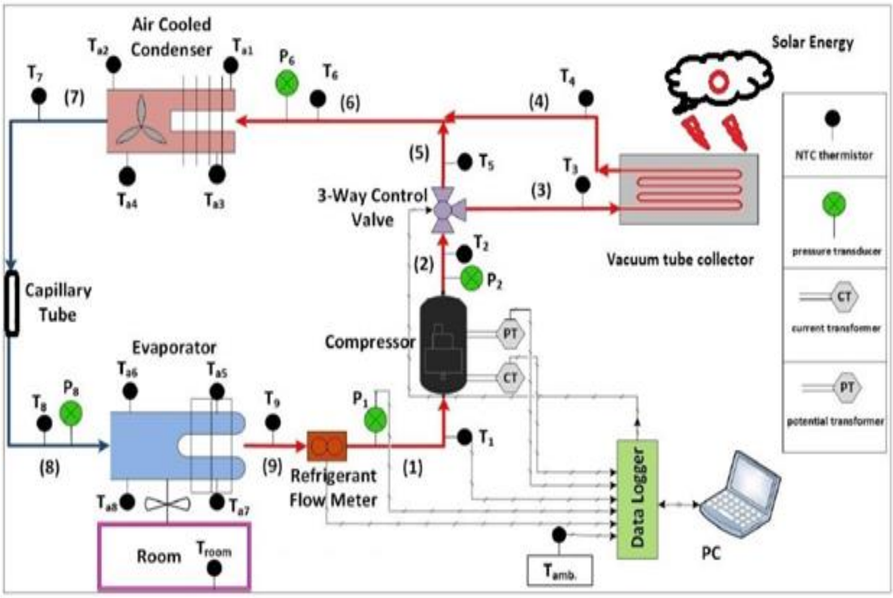

Figure 7. Control diagram of solar thermal air conditioning system.

6. Conclusion

To summarise, the introduction of a solar-thermal hybrid air conditioning system offers a hopeful resolution to tackle the issue of energy saving in residential buildings in Muscat. This system utilises renewable solar energy as a means of cooling, providing a sustainable alternative to traditional cooling methods. This not only helps to save the environment but also enhances energy efficiency.

The main goal of this study is to improve the effectiveness of split AC systems and optimise energy conservation in areas with elevated ambient temperatures.

One of the main tactics is to combine a solar collector vacuum tube with the air conditioning system to maximise performance and enhance energy efficiency.

Performing empirical and quantitative comparisons of standard and split air conditioning systems.

This study aims to improve the thermal efficiency and decrease power usage in Muscat by using a thermal-solar air conditioning system.

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