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Experimental Determination of the Minimum Frost-Free Evaporating Temperature in a Cooling Coil

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Abstract

The objective of the study is to verify the performance and operational efficiency of prototype evaporator coil designed for multipurpose applications, including ventilation, air conditioning, and air quality control. As cooling systems play a critical role in maintaining indoor environmental quality in residential, commercial, and industrial settings, ensuring the reliability and functionality of such a prototype is essential before broader deployment or further development. The study holds particular significance for industries such as pharmaceuticals, chemicals, fertilizers, etc. where maintaining a supply of low-moisture air is essential to avoid the formation of product clumps, inconsistencies in the products and efficient drying thereby increasing its shelf life. In these contexts, it is crucial that the humidity ratio of the process air remains within the prescribed limit to comply with operational and product quality standards. The primary objective of the research is to determine the lowest evaporating refrigerant temperature at which the system can function reliably without frost accumulating on the evaporator surface, even in the presence of high moisture content in the incoming air. The formation of frost adversely affects heat transfer efficiency, impedes airflow, and may result in system shutdowns problems that are intolerable in sensitive industrial settings.

1. Introduction

In several industrial processes, especially those involving storage and packaging, environmental control plays a vital role in preserving product quality. Among these, the fertilizer industry has particularly stringent requirements for temperature and humidity regulation. Fertilizers tend to absorb moisture from the surrounding air, which leads to clumping, chemical degradation, and difficulty in handling. To prevent this, air with low relative humidity (RH) and a consistently high temperature (around 40°C) is required in the

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storage areas. To achieve such conditions, Air Handling Units (AHUs) are widely used. AHUs are responsible for conditioning the air by performing operations like cooling, dehumidification, reheating, and air distribution. In this study, the focus lies on cooling and dehumidification, which are essential before reheating the air to 40 °C. Dehumidification is achieved through cooling the air below its dew point temperature, allowing moisture to condense and be removed. However, to ensure deep dehumidification suitable for fertilizer storage, the air must be cooled to around 2 °C. Achieving such low outlet temperatures often leads to a serious issue: frost formation on the evaporator coil. Frost acts as an insulator, reducing heat transfer, restricting airflow, and eventually leading to operational inefficiency or system breakdown. To tackle this, a dual-evaporator system is used in our project. The first evaporator coil brings down the air temperature from ambient (typically 25–30 °C) to around 10 °C or slightly below. The second evaporator coil then cools the air further to the required 2 °C. After this cooling and moisture removal, the air is reheated to 40°C in the AHU. This staged cooling process reduces the load on individual coils and helps in achieving lower RH more effectively. Additionally, a hot gas bypass valve is incorporated into the system. It diverts a portion of the hot refrigerant gas back into the evaporator during low-load conditions, helping to maintain the evaporator temperature and prevent it from dropping too low, which can trigger frosting.

2. Literature Review

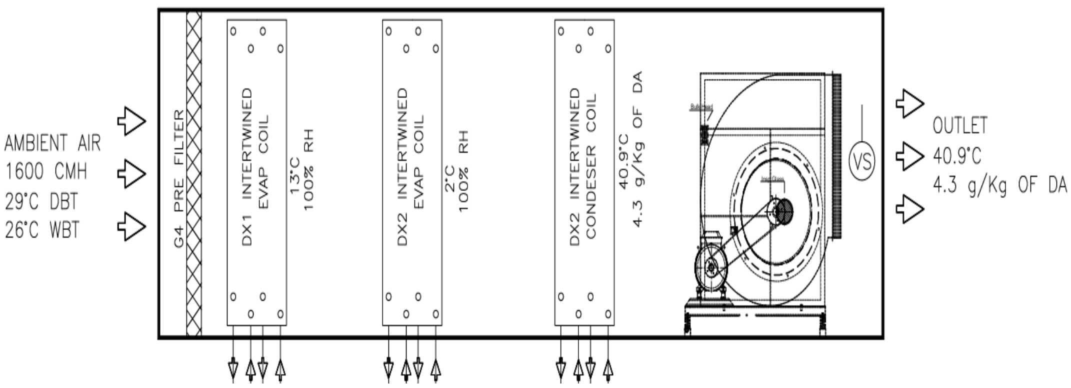
Frost formation is a persistent and challenging phenomenon in the operation of air-source heat pumps (ASHPs) and HVAC systems, especially when functioning in regions characterized by hot summers and cold winters. In these transitional climates, the temperature and humidity conditions are often conducive to the development of frost on the surface of evaporator coils, significantly impeding system performance. Frost accumulation increases thermal resistance and restricts heat exchange efficiency, ultimately leading to higher energy consumption and reduced equipment life. As such, both passive and active strategies for frost prevention and control have become a core focus of research and development in thermal system engineering. Recent studies on the anti-frosting capabilities of heat pump evaporators operating in diverse climate zones have highlighted that surface characteristics and refrigerant flow patterns are key factors influencing frost behaviour. Optimized fin surface geometry, improved coil design, and adaptive defrost scheduling based on real-time environmental inputs were found to be effective in enhancing evaporator resilience against frosting [1]. The research revealed that in regions experiencing sharp diurnal temperature variations, a tailored system design that adapts to ambient shifts can significantly improve system efficiency by minimizing unnecessary defrost cycles. Mathematical modelling has emerged as a powerful tool for understanding and predicting frost growth on heat exchanger surfaces. Advanced models now consider dynamic parameters such as air velocity, coil surface temperature, humidity, and frost thermal conductivity. These models are capable of simulating frost layer development over time, offering insights into the point at which frost begins to adversely affect system performance [2]. Such predictive modelling supports proactive defrosting and can be integrated into control logic to trigger defrost only when performance degradation reaches a threshold, thereby avoiding energy wastage associated with fixed-interval defrosting. Emerging technologies have introduced innovative approaches for active frost control. One such approach involves the application of an electric field to evaporator coils. By influencing the migration and distribution of water molecules on the coil surface, this method can delay the onset of frost and reduce the overall density of the frost layer [3]. While still in the experimental phase, this approach shows promise for systems where traditional defrosting mechanisms may be energy-intensive or infeasible. It also opens up avenues for further exploration into electro-thermal interactions on coil surfaces. In industrial settings, simpler mechanical methods have proven effective in maintaining evaporator performance during frosting conditions. For instance, adjusting airflow rates, manipulating refrigerant charge, and employing differential temperature-based triggers for defrosting are strategies that have yielded consistent improvements [4]. These methods are often implemented through control retrofits rather than hardware modifications, making them cost-effective for existing installations. Among various defrosting strategies, hot-gas bypass (HGB) has been one of the most widely adopted solutions in HVAC and refrigeration systems. This technique involves rerouting hot discharge gas from the compressor to the evaporator during a defrost cycle, allowing the system to melt accumulated frost without reversing the entire refrigeration cycle. Enhancements to this method have been achieved by introducing dual hot-gas bypass arrangements, which offer better defrost uniformity and improved energy management [5]. The use of dual bypass valves enables more accurate control over gas injection, ensuring that frost removal occurs evenly across the evaporator surface. Moreover, the combination of hot-gas bypass with variable outdoor fan speed has shown considerable promise. By modulating the fan speed during defrost, it is possible to regulate the airside heat transfer rate, which in turn affects how quickly and uniformly the frost is removed. This method helps in avoiding partial defrosts, which could otherwise lead to rapid reformation of frost and degrade thermal performance. It also reduces the mechanical load on fans and compressors, extending their operational life [6]. To support these technical innovations, recent reviews of frost prevention strategies have consolidated various active and passive approaches. These include surface coatings designed to repel moisture, use of thermoelectric modules for localized heating, and adaptive control algorithms that rely on environmental sensors to make real-time decisions [7].

The integration of multiple techniques into hybrid systems has become increasingly common, especially in systems operating in highly variable climates. Such hybrid approaches are often governed by centralized control units that balance energy input, humidity levels, and thermal load requirements. In ventilation systems utilizing cross-flow or counter-flow heat exchangers, frost protection becomes particularly important during winter when temperature differentials are large. Studies have demonstrated that bypass systems integrated into these exchangers can effectively channel part of the airstream away from the freezing zones, thereby preventing the conditions necessary for frost to form [8]. These designs are often complemented by periodic warm air injection or pre-heating of the incoming air stream to maintain exchanger efficiency. In cold-climate residential settings, especially those employing energy recovery ventilators (ERVs) or heat recovery ventilators (HRVs), frost poses a significant threat to consistent indoor comfort. Design modifications that incorporate passive defrost paths, pre-conditioning air modules, or scheduled airflow reversal mechanisms have shown measurable benefits. More recent advancements suggest that adding a smart controller that assesses outdoor air temperature and humidity trends can dynamically switch between heating modes and bypass modes, thus preventing frost without sacrificing heat recovery [9]. In the broader context of ventilation systems, a comprehensive review of heat recovery technologies has emphasized the importance of frost control, particularly in energy recovery ventilators (ERVs) and heat recovery ventilators (HRVs) operating in cold climates. Frost buildup in these systems not only hampers thermal recovery efficiency but can also lead to flow blockages and increased maintenance needs. The review compiled findings from multiple sources and concluded that hybrid heat recovery systems combining sensible and latent heat exchangers with frost bypass channels or preheaters offer superior performance [10]. It also stressed the need for integrating frost detection sensors and adaptive airflow rerouting mechanisms to maintain continuous operation. These strategies are vital for ensuring consistent indoor air quality and energy efficiency in residential and commercial buildings located in cold regions. Experimental investigations into the performance of fresh air handling units (FAHUs) have brought to light the critical influence of frost formation on their cooling capabilities and overall energy efficiency. In FAHUs that operate under humid and subfreezing conditions, the high latent load due to moisture rich air causes rapid frost accumulation on evaporator coils, particularly during the initial minutes of system start-up or after defrost cycles. Studies have shown that if the coil surface temperature drops even marginally below the freezing point, thin frost layers start to nucleate, which quickly grow and spread across the finned surfaces [11].

3. Materials and Methods

The primary objective of this project is to identify the lowest practical evaporator coil temperature at which a refrigeration-based Air Handling Unit (AHU) system can operate without inducing frost formation on the coil, while still delivering sufficiently dehumidified air with an outlet temperature close to 2 °C. This temperature target is particularly important for applications such as fertilizer storage, where both humidity and temperature must be strictly regulated to maintain the quality and stability of the stored material.

Fig.1. Schematic of Air Handling Unit



Operating the evaporator at low temperatures increases the system's ability to remove moisture from the air; however, it also raises the risk of frost formation on the coil surface. Frost accumulation can reduce heat transfer efficiency, obstruct airflow, and lead to frequent system maintenance or shutdowns. Hence, a key challenge in this project is to determine the safe lower operating limit for the evaporator temperature that provides effective dehumidification while preventing coil frosting.

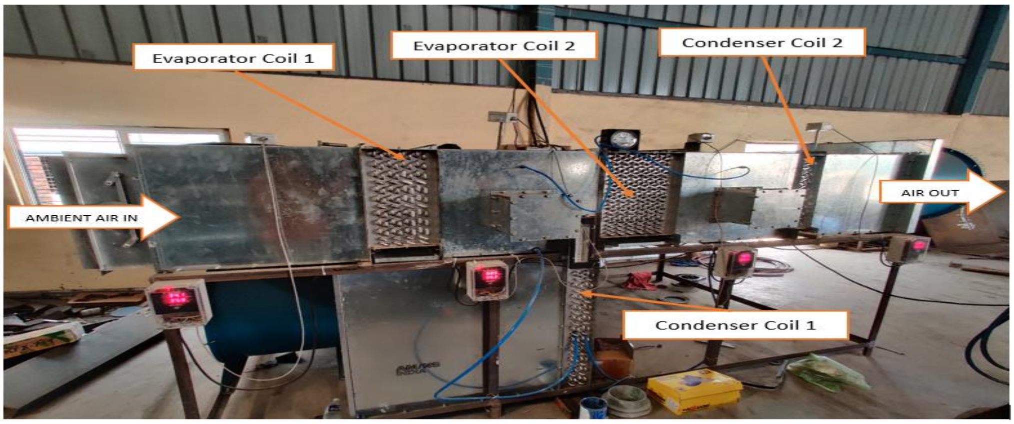


Fig.2. Actual photograph of air handling unit

The research investigates the performance of an AHU system designed with a dual-stage evaporator coil setup, enabling staged cooling. This configuration allows the air to be cooled in two steps, thereby enhancing the moisture removal capacity of the system. A reheating mechanism is applied after dehumidification to bring the air back to the desired delivery temperature, minimizing the risk of condensation in the storage area. Another focus of the project is to evaluate the role of a hot gas bypass valve, which is used to control refrigerant flow during partial load conditions. By diverting a portion of the refrigerant away from the evaporator, the valve helps maintain stable coil temperatures and prevents freezing under low cooling demands. The project is based on a series of experimental trials that monitor the system's behavior under varying thermal and airflow conditions. Key parameters such as coil surface temperature, air temperature and humidity, system pressures, and energy consumption are recorded and analyzed. This data-driven approach aims to define optimal operating points and control strategies for achieving both energy efficiency and operational reliability. In the end, the objective is to derive actionable design insights that will guide the development of efficient, application-specific AHUs capable of maintaining precise environmental conditions. The results will have direct applicability not only in fertilizer storage but also in other industrial scenarios that require strict humidity and temperature control, such as pharmaceutical storage, clean rooms, and low-temperature process environments.

3.1 Principle of operation

The Air Handling Unit (AHU) developed in this research operates on the principle of controlled air treatment through staged cooling, dehumidification, and sensible reheating. It is designed to serve environments like fertilizer storage facilities, where strict control over temperature and humidity is essential to prevent product degradation. Ambient air contains both sensible heat (temperature) and latent heat (moisture content). The system works by removing both these components in a controlled, staged manner using refrigeration-based cooling coils. The dehumidification is achieved by cooling the air below its dew point, which forces moisture to condense out of the air. However, this also lowers the air temperature beyond the required level. Therefore, a final reheating stage is employed to bring the air back to a specified delivery temperature without reintroducing moisture. The system utilizes two independent refrigeration circuits working in series. The first stage brings down the bulk of the temperature and moisture, while the second stage performs fine dehumidification. The final heating is achieved not by a separate heater, but by reclaiming heat from the condenser of the second refrigeration system—thus improving overall energy efficiency. Additionally, the system is equipped with Hot Gas Bypass Valves (HGBVs) and Electronic Expansion Valves (EEVs) to maintain coil temperatures within a safe range and avoid frost formation, especially under part-load conditions or when airflow velocity drops. By integrating precision control mechanisms, multi-stage cooling, and waste heat recovery, the AHU operates as a closed-loop system capable of consistently delivering dry, temperature-controlled air under varying external and internal load conditions.

3.2 Airflow circuit

The air is cooled from ambient conditions (approximately 32 °C dry bulb) to around 13 °C. During this process, the relative humidity of the air increases and reaches saturation at 100%. The reduction in temperature causes moisture from the air to condense on the coil surface, reducing the specific humidity from 0.02135 to 0.00933 kg/kg of dry air. The bypass factor of this coil is 0.1, indicating that 10% of the air does not interact thermally with the coil. This stage removes a large portion of the moisture and lowers the air temperature significantly without the risk of frost formation, as the coil surface temperature remains above 7 °C. The air exiting the first coil, now saturated at 13 °C, flows into the second evaporator coil for further cooling. This coil brings the air temperature down to 2 °C while maintaining 100% relative humidity. The specific humidity drops slightly further, from 0.00933 to approximately 0.0093 kg/kg of dry air. This stage is more sensitive to frosting, as the coil operates with a surface temperature near -4 °C. Hence, frost control measures like hot gas bypass valves and electronic expansion valves are actively used. The bypass factor of this coil is 0.05, indicating a more effective heat exchange as 95% of the airflow is in contact with the coil surface. After the air has been cooled and dehumidified, it is reheated to the final delivery condition. This is achieved not by a separate heating element but by placing the condenser coil of refrigeration system 2 directly in the air path. The cold, dry air absorbs the waste heat from the condenser, raising its temperature from 2 °C to approximately 40.9 °C. This process is purely sensible heating, meaning there is no change in the specific humidity (which remains around 0.00436 kg/kg), but the relative humidity drops significantly to about 8.4%. This reheating strategy is highly energy-efficient, as it utilizes the heat already generated in the refrigeration cycle, eliminating the need for additional electric heating elements. The final treated air, now at the target temperature and low humidity, is delivered to the storage space via the supply duct. It meets all the environmental conditions required for fertilizer preservation, such as high temperature, low moisture content, and stable airflow.

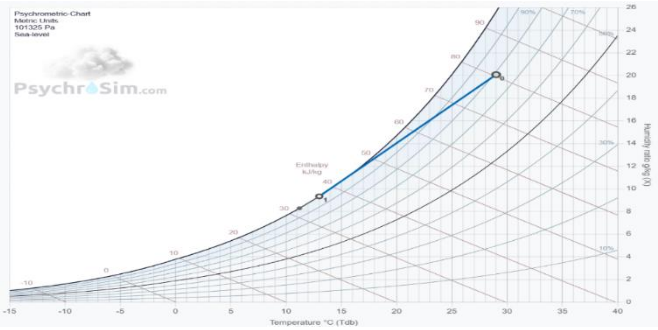


Fig. 3. Psychrometric calculations for cooling with dehumidification

T_{DBT} = 29 ° C, ω1 = 0.002135 kg/kg, h1= 83.7 kJ/kg, T_{WBT} = 26 ° C, Q = 1600 m³/hr = 26.6 m³/min

Conditions After Evaporator 1:

T_{DBT} = 13° C ω2 = 0.00933 kg/kg, h2 = 36.6 kJ/kg, Relative Humidity (RH)= 100 %

Room Total Heat (RTH) = Room Sensible Heat (RSH) + Room Latent heat (RLH)

= (0.02044 x Q x ΔT_{DBT}) + (50 x Q x **Δω**) = RTH = (0.02 x Q x Δh)

RTH = 0.02 x Q x Δh = 0.02 x 26.6 x (83.7-36.6) = 25.057 KW

= (25.057/3.517) = 7.12 TR ≈ 7 TR (Total Cooling Load for Coil 1)

Theoretically from these calculations we can conclude that a refrigerator of approximately 7 TR capacity is necessary to cool and simultaneously dehumidify the air from 26° C to 13° C with dehumidification. At outlet the desired air temperature is 13° C but with 100 % Relative

$$BF = \frac{t_{air\ leaving} - t_{adp}}{t_{air\ entering} - t_{adp}} = \frac{t_2 - t_{adp}}{t_1 - t_{adp}}$$

For Evaporator Coil 1, Evaporator Efficacy = 90 %, BPF = 10 % = 0.1, BPF = $\frac{13-ADP}{29-ADP}$ = 0.1

Solving we get, ADP = 11.22 ° C, Dehumidification Rate in coil 1, **Δω** = ω1- ω2 = 0.02135 - 0.00933 = 0.01202 kg/kg = 12.02 g/kg, Theoretically, Coil Surface Temperature = Apparatus Dew Point temperature. To achieve required cooling and Dehumidification process., Hence, T_{Coil} = 11.22 ° C. Practically the approach temperature of the refrigeration coil or refrigerant is 4 ° C less than that of the coil surface temperature accounting for factors like thermal storage, thermal conductivity of the material and fouling factors. Therefore,

$T_{Evaporator\ 2}$ = T_{Coil} - 4 = 11.22 – 4 = 7.22 ° C,

T_{DBT} = 13° C ω2 = 0.00933 kg/kg of d.a. h2= 36.6 KJ/kg

T_{WBT} = 13° C, Q2= 1506 m³/hr = 25.1 m³/min

Conditions After Evaporator 2:

T_{DBT} = 2° C ω3 = 0.00436 Kg/kg of d.a. = 4.36 g/kg, Relative Humidity (RH) = 100 %

Room Total Heat (RTH) = Room Sensible Heat (RSH) + Room Latent heat (RLH)

= (0.02044 x Q x ΔT_{DBT}) + (50 x Q x Δ**ω**), RTH = (0.02 x Q x Δh), RTH = 0.02 x Q x ΔT = 0.02 x 25.1 x (36.6 - 12.9) = 11.8974 kW = (11.8974/3.517)= 3.38 TR ≈ 3 or 3.5 TR (Total Cooling Load for Coil 2)

Theoretically from these calculations we can conclude that a refrigerator of approximately 4 TR capacity is necessary to cool and simultaneously dehumidify the air from 13° C to 2° C with dehumidification on the second stage of cooling. At outlet the desired air temperature is 2° C but with 100 % Relative Humidity.

Mathematically,

$$BF = \frac{t_{air\ leaving} - t_{adp}}{t_{air\ entering} - t_{adp}} = \frac{t_2 - t_{adp}}{t_1 - t_{adp}}$$

For Evaporator Coil 1, Evaporator Efficacy = 95 %, BPF = 5 % = 0.05

BPF = $\frac{2-ADP}{13-ADP}$ = 0.05, Solving we get, ADP =1.42° C

Dehumidification Rate in coil 1, Δ**ω** = ω1- ω2 = 0.00933 - 0.00436 = 4.97x10^{-3} kg/kg = 4.97 g/kg, Theoretically, Coil Surface Temperature = Apparatus Dew Point temperature. To achieve required cooling and Dehumidification process. Hence, T_{Coil} = 1.42 °C. Practically the approach temperature of the refrigeration coil or refrigerant is 4 ° C less than that of the coil surface temperature accounting for factors like thermal storage, thermal conductivity of the material and fouling factors. Therefore, $T_{Evaporator\ 2}$ = T_{Coil} - 4 = 1.42 – 4 = -2.58 ° C.

4 Conclusions

The project aimed at designing, developing, and testing a specialized Air Handling Unit tailored for precision climate control in industrial environments particularly for fertilizer storage, where maintaining low humidity is essential to prevent clumping and chemical degradation. The final prototype met all design objectives successfully. It integrates standard HVAC components filters, dual evaporator coils, dual refrigeration systems, expansion valves (both thermostatic and electronic), hot gas bypass valves, suction pressure controllers, and a condenser-based reheating mechanism into a compact and energy-efficient unit. The modular structure allows for easy installation, maintenance, and customization based on application-specific requirements. The intelligent use of an electronic expansion valve (EEV) and automated hot gas bypass logic allowed the system to handle load fluctuations without sacrificing performance. Additionally, replacing electric reheaters with condenser heat recovery reduced operational costs, marking a sustainable design decision. The project also explored the real-world implementation challenges, including airflow management, frosting tendencies, and control response under transient conditions. By conducting multiple experimental trials and collecting real-time performance data, the team ensured that the system was not only theoretically sound but also practically viable. Furthermore, this project highlights the potential for scalable manufacturing due to its relatively simple construction, cost-effectiveness, and use of commercially available components. It holds strong potential for deployment in fertilizer and agrochemical storage, pharmaceutical warehouses, precision-controlled cold rooms, data centers requiring dry air cooling and industrial drying processes.

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