

DESIGN AND EVALUATION OF A HEAT PUMP DRYING SYSTEM USING REPURPOSED AIR CONDITIONING COMPONENTS

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ABSTRACT

Heat pump drying presents an environmentally friendly alternative to traditional drying methods. As discarded air conditioners and refrigerators increasingly contribute to electronic waste, this research explores the potential of repurposing components from old air conditioning systems to construct a heat pump drying system. The study involved three no-load trial sets. Key findings emphasize the importance of releasing excess heat to the environment via a sub-condenser for maintaining system stability and operational safety, as observed in Trial 3.1. Additionally, in Trial 3.2, without an electric heater, the inlet drying airflow temperature ranged only from 37 °C to 44 °C. Following this, in Trial 3.3, with the heater at 50% capacity, the temperature reached 50 °C to 56 °C. Overall, this research highlights the feasibility of repurposing air conditioning systems to develop efficient and cost-effective heat pump drying systems.

Keywords: Heat pump drying (HPD), drying system design, refrigeration unit reuse, sub-condenser.

1. INTRODUCTION

Drying is a crucial process across numerous industries, facilitating preservation, processing, and quality enhancement of products. Drying procedures in the food industry can be categorized into three main areas: (a) economic considerations, (b) environmental concerns, and (c) product quality aspects [1] [2]. Notably, global electricity demand and costs are escalating, and environmental issues are becoming increasingly urgent [3]. Conventional drying methods, however, often consume substantial amounts of energy, posing challenges to efficiency and sustainability [4]. High-temperature drying, while rapid and suitable for many materials, can degrade the quality of heat-sensitive products [5]. Conversely, low-temperature vacuum drying (freeze drying) better preserves product quality but demands high energy costs and complex equipment [5].

Energy efficiency of a dryer is measured by the specific moisture extraction rate (SMER), defined as the mass of water removed per unit of energy consumed [5]. As shown in Table 1, the SMER values typically range from 0.1 to 0.7, indicating low thermal efficiency, particularly for freeze dryers, at only 0.08 kg/kWh.

Table 1. Energy utilization and SMER of commercial dryers [5]

Type of dryers	Minimum energy [kJ/kg]	Maximum energy [kJ/kg]	Average SMER [kg/kWh]
Vacuum freeze	45,000	115,000	0.08
Rotary	4600	9200	0.52
Spray	4500	11,500	0.45
Tunnel	5500	6000	0.63
Band	4000	6000	0.72
Fluidized bed	4000	6000	0.72

To address these limitations, heat pump drying (HPD) systems have emerged as a promising alternative, offering advantages such as energy savings and efficient utilization of the heating and

cooling capabilities of a heat pump system [6] [7]. For example, an adiabatic heat pump fluidized bed dryer exhibits SMER and energy usage of 2 - 3 and 1200 - 1800 kJ/kg, respectively [5]. This shows that the SMER is equivalent to or higher than traditional drying methods, while the energy usage is lower. Furthermore, studies have demonstrated that HPD can achieve drying efficiencies up to 95%, surpassing vacuum drying (70%) and conventional hot air drying (35 - 40%) [8]. Additionally, Pendyala et al. investigated the economic feasibility of HPD for agricultural products and concluded that it is particularly effective for materials with high initial moisture content and in regions with high ambient humidity [9], making HPD highly suitable for Vietnam's hot and humid climate.

The air conditioning market in Vietnam is projected to experience significant growth, from USD 1.02 billion in 2024 to USD 2.89 billion in 2030, with an annual growth rate of nearly 8% [10]. However, this development also leads to an increase in electronic waste, particularly discarded air conditioning systems and refrigerators. It is estimated that the amount of major household appliances discarded in Vietnam by 2025 will be substantial: approximately 200,000 tons of refrigerators (averaging 43 kg/unit) and about 20,000 tons of air conditioners (averaging 40 kg/unit) [11] [12]. To handle these discarded air conditioning systems, there are three main methods: disposal as regular household waste, collection by collectors, or reuse [13]. Reuse or refurbishment can contribute to reducing this waste and minimizing environmental impact.

In this context, repurposing components from used air conditioning and refrigeration systems to construct HPD systems presents an innovative solution. This approach not only mitigates electronic waste but also utilizes available components, reduces production costs, and contributes to environmental protection. Therefore, this study focuses on designing and evaluating the operational capability of an HPD system built from recycled air conditioning components, ensuring feasibility, safety, and effectiveness in practical applications. Three sets of no-load trials were designed under various operating conditions, specifically examining the absence of a sub-condenser and/or an electric heater. The results demonstrate the successful construction of the system, with key findings including the necessity of a sub-condenser for stable operation and the ability to elevate the drying airflow temperature from 37 - 44 °C to 50 - 56 °C using an electric heater, thereby expanding the system's applicability.

2. METHOD

2.1. Experimental setup

2.1.1. System and process description

HPD systems are designed to recover heat from the exhaust vapor, which is typically lost in conventional dryers. A well-designed system operates in a closed loop, maximizing energy recovery for both heating and cooling during the drying process. This is achieved as the refrigerant absorbs latent heat from the exhaust vapor in the evaporator and releases it in the condenser [14]. The HPD system in this study was designed based on this efficiency principle.

The HPD model was constructed with two primary loops, shown in Figure 1: the air loop and the refrigerant loop. The air loop, located in the upper part of the diagram, circulates warm and dry air to the drying chamber. The moisture extracted from the material is condensed at the evaporator (EVA) and removed naturally through a drain line, reducing absolute humidity. Through Condenser-2 (COND-2 - as the main condenser of the system) and the electric heater (EH – as an additional heat source), dry bulb temperature (DBT) is increased and relative humidity (RH) is decreased, driving the drying process.

The lower part of the diagram illustrates a basic single-stage vapor compression refrigeration system, with R22 as the working fluid. It includes the following components: a compressor (COMP), two condensers: Condenser-1 (COND-1 - as the sub-condenser of the system) and COND-2, a capillary coil (as the expansion device), and EVA. The refrigerant flowing inside the tubes in EVA and COND-2 exchanges heat with the air flowing outside the tubes. Therefore, the connection between the two loops is facilitated by an energy exchange mechanism.

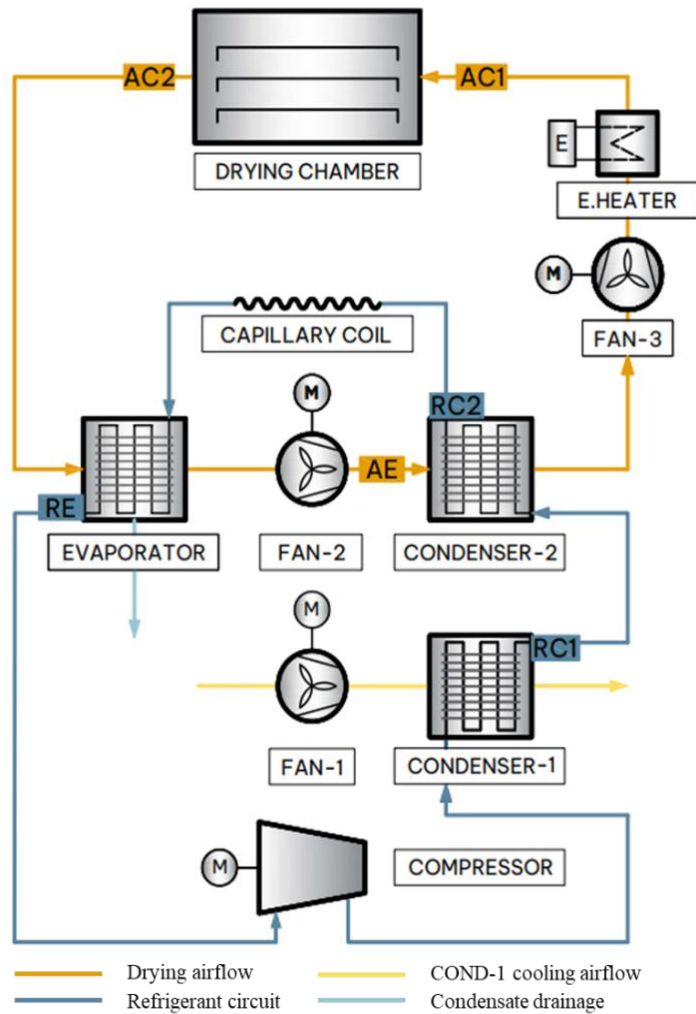


Figure 1. HPD system schematic

2.1.2. System specifications

Drying chamber and refrigeration cycle

The drying chamber, designed as a rectangular prism, has internal dimensions of 50 cm $\times$ 40 cm $\times$ 30 cm. It is equipped with four trays, each constructed from durable stainless steel 316 and measuring 40 cm $\times$ 30 cm. Airflow is facilitated by rectangular inlet and outlet ports, each with a cross-sectional area of 25 cm $\times$ 20 cm. In the refrigeration cycle, COMP has a capacity of 1 HP and is a rotary type. The heat exchangers, including COND-1, COND-2, and EVA, are all finned tube types, using copper tubes and aluminum fins. Finally, the capillary coil, made of copper, features a very small diameter, creating a pressure drop essential for the refrigeration cycle.

Measurement instrumentation

The measurement setup is summarized in Table 2, including the devices used at each sensor location and the corresponding parameters. Specifically, the SHT30 sensors were utilized to measure DBT and RH of the drying air at the inlet and outlet of the drying chamber, and after EVA. For the refrigerant, the DS18B20 sensors were used to measure temperature of the tube's surface of these heat exchangers.

While the system was equipped with many sensors, this study focused on the DBT_{ACI} , T_{RC1} , and T_{RC2} parameters. Data collected from the remaining sensors can be utilized for future in-depth studies.

Table 2. Measurement instrumentation

Location	To measure	Model	Measurement range ^a	Accuracy ^b
AC1	Drying air's DBT and RH before the drying chamber	SHT30	T: -40 - 120 °C RH: 0 - 100%	±0.3 °C (0 - 65 °C) ±3% (10 - 90%)
AC2	Drying air's DBT and RH after the drying chamber			
AE	Drying air's DBT and RH after EVA			
RC1	Refrigerant temperature at COND-1's outlet ^c	DS18B20	T: -50 - 125 °C	±0.4 °C (-10 - 70 °C)
RC2	Refrigerant temperature at COND-2's outlet ^d			
RE	Refrigerant temperature at EVA's outlet ^e			
^{a,b} Information obtained from sensor manufacturers' datasheets.				
^{c,d,e} The sensors are affixed to the outer surface of the tube using thermal grease, ensuring intimate contact. Consequently, the measured temperature can be considered representative of the refrigerant temperature.				

2.2. System testing methodology

The components directly influencing the drying airflow are EVA and COND-2, while EH provides supplementary heating. For operational stability, existing systems typically use a sub-condenser for heat exchange with the ambient air or place the condenser outside the drying airflow cycle [5] [14].

To qualitatively evaluate the system's stability and thermal equilibrium under different operating conditions, particularly in scenarios devoid of COND-1 and/or EH, a series of experiments was conducted. These experiments were structured into three distinct sets, each comprising three individual trials:

Trial 1.x (EH off and isolated COND-1):

In these initial trials, EH was turned off, and COND-1 was completely insulated to prevent any heat exchange with the environment. Its fan (F-1) was also off, simulating a system without COND-1. COND-2's fan (F-3) was then increased in 25% increments, from 50% to 100% capacity, to observe the system's response.

Trial 2.x (EH off and uninsulated COND-1):

Subsequently, EH remained off, but COND-1 was allowed to exchange heat with the surrounding air. In these trials, F-3's manipulated variable percentage (MV) was held constant at 50% to concentrate on evaluating how different levels of heat exchange between COND-1 and the environment affected system stability, with MV_{F-1} set at three levels: 50%, 75%, and 100%.

Trial 3.x (EH on and uninsulated COND-1):

Finally, EH was on, and COND-1 was allowed to exchange heat with the environment. The fans' MV values in these trials were set to match those used in Trial 2.x.

These trials are explained in more detail in Table 3.

Table 3. System testing methodology

Component	Trial 1.x			Trial 2.x			Trial 3.x		
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
COMP [On/Off]	On	On	On	On	On	On	On	On	On
COND-1 [Yes/No] ^a	No	No	No	No	No	No	Yes	Yes	Yes
MV _{EH} [%]	0	0	0	0	0	0	50	50	50
MV _{F-1} [%]	0	0	0	50	75	100	50	75	100
MV _{F-2} [%]	50	50	50	50	50	50	50	50	50
MV _{F-3} [%]	50	75	100	50	50	50	50	50	50
^a Yes = Heat exchange allowed, No = No heat exchange									

To ensure operational safety, the trials were stopped when T_{RC1} reached approximately 70 °C. For the remaining experiments, they were stopped when the temperature values remained constant over time.

A flowchart illustrating the experimental procedure for each trial set is presented in Figure 2. This flowchart outlines the operational sequence, decision points, and termination criteria for each trial scenario.

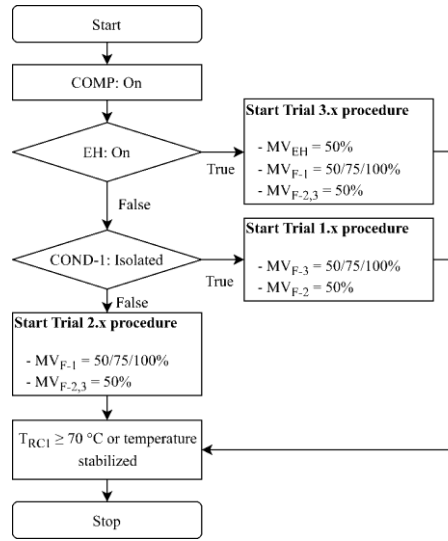


Figure 2. Flowchart of experimental testing methodology

3. RESULTS AND DISCUSSION

In Trial 1.x, as illustrated in Figure 3, T_{RC1} exhibited a continuous rise. Specifically, T_{RC1} experienced a rapid increase in temperature during the initial phase, with the rate of increase slowing down and stabilizing in the later stage. This is because the refrigerant entering COMP was initially at room temperature, but later decreased in temperature due to the capillary coil taking effect.

For Trial 1.1, when MV_{F-3} was only at 50%, the increase in T_{RC1} caused an increase in both DBT_{AC1} and T_{RC2} . However, upon increasing MV_{F-3} to 75% and 100% in Trials 1.2 and 1.3, respectively, an enhancement in the heat exchange efficiency between the drying airflow and devices such as COND-2 and EVA was observed, consequently resulting in a slight increase or a decreasing trend in T_{RC2} and DBT_{AC1} . The accelerated heat exchange process progressively shortened the time for T_{RC1} to reach 70 °C, from an initial 400 s in Trial 1.1, to 280 s in Trial 1.2, and finally to 190 s in Trial 1.3.

The isolation of COND-1 led to heat accumulation within the system. This phenomenon can be explained through the following equations:

$$W_{COMP} = Q_{COND-1} + Q_{COND-2} - Q_{EVA} \quad (1)$$

This equation means that the compressor's work is the difference between the heat released at both COND-1 and COND-2, and the heat absorbed at EVA [15] [16].

Assuming that heat loss is negligible, to prevent heat accumulation and maintain thermal stability, drying airflow equilibrium must be ensured:

$$Q_{EVA} - Q_{COND-2} = 0 \quad (2)$$

Consequently,

$$W_{COMP} = Q_{COND-1} \quad (3)$$

Equation 3 demonstrates that the compressor power is converted into heat and must be released to the environment. Otherwise, heat in the system accumulates continuously. When COND-1 is isolated, the heat exchange with the surrounding air at that location becomes negligible, resulting in a Q_{COND-1} value of approximately zero. This contradicts Equation 3, since the continuously operating compressor converts work into heat, which must be released at COND-1, Q_{COND-1} cannot be zero.

Therefore, COND-1 is an essential component for ensuring system stability and safety.

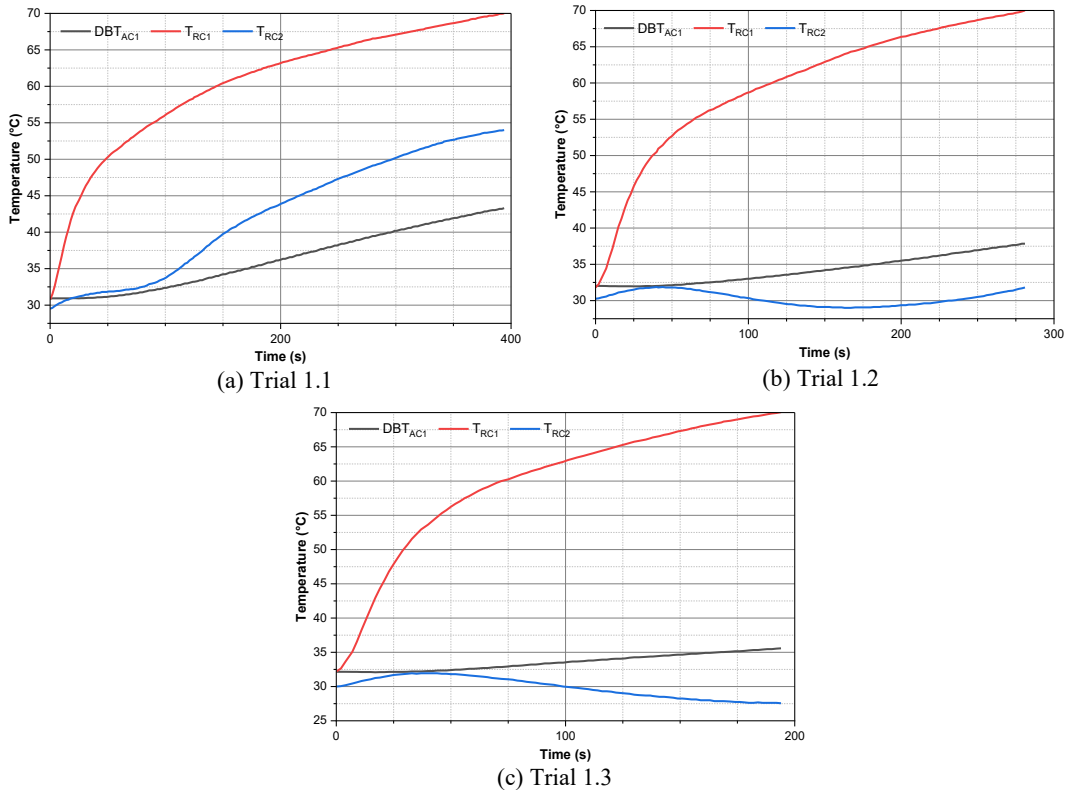


Figure 3. Changes over time of DBT_{AC1} , T_{RC1} , and T_{RC2} in Trial 1.x

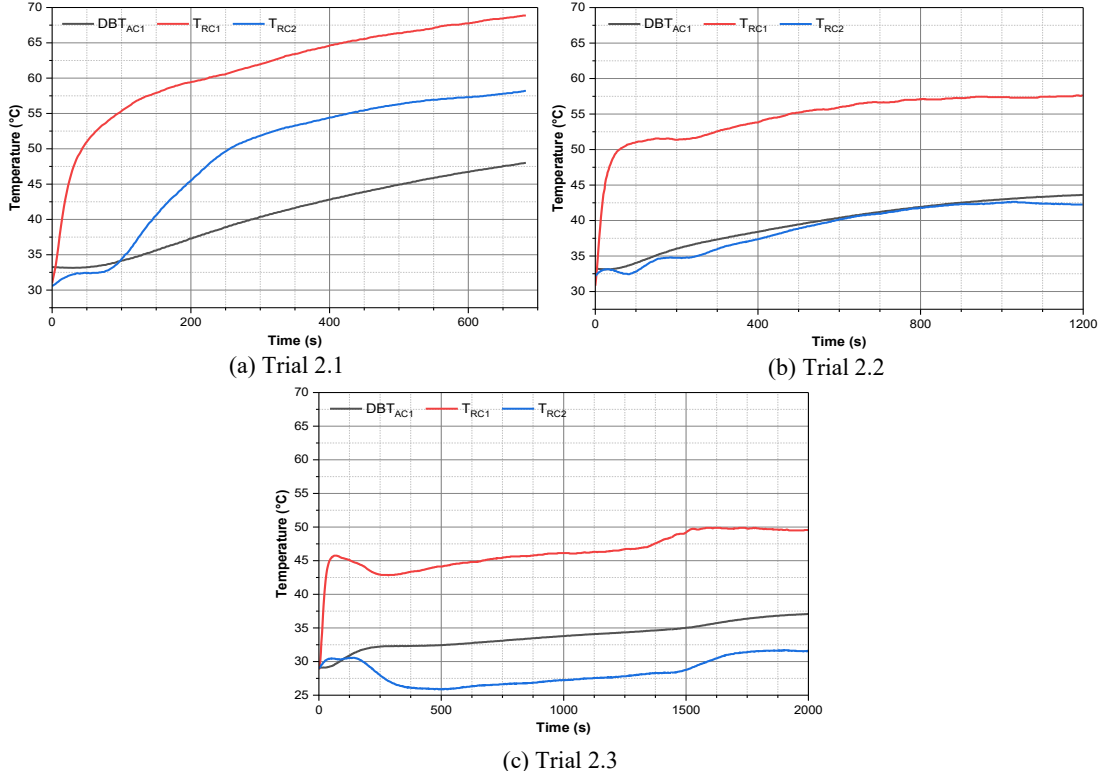


Figure 4. Changes over time of DBT_{AC1} , T_{RC1} , and T_{RC2} in Trial 2.x

Following Trial 1.x, Trial 2.x focused on evaluating the temperature changes in the system as MV_{F-1} was progressively increased. The detailed measurement results are presented in Figure 4. The results indicate that at 50% of F-1's capacity (Trial 2.1), the system's ability to remove heat was insufficient. Furthermore, the time taken for T_{RC1} to reach 70 °C in Trial 2.1 was nearly double that in Trial 1.1. This suggests that although the system did not achieve thermal equilibrium, allowing COND-1 to exchange heat with the environment contributed to slowing down the rate of temperature increase in T_{RC1} . With MV_{F-1} at 75% and 100% (Trial 2.2 and Trial 2.3), stable temperatures were achieved, namely T_{RC1} at 58 °C and 50 °C, T_{RC2} at 42 °C and 32 °C, and DBT_{AC1} at 44 °C and 37 °C, respectively.

These results confirm the ability to establish thermal equilibrium under various operating conditions, depending on the amount of heat released from the system by COND-1. Higher heat dissipation rates resulted in lower equilibrium points. Additionally, DBT_{AC1} only reached 37 - 44 °C, which is insufficient for drying processes requiring higher temperatures. Therefore, adding an electric heater to the system is necessary to improve its efficiency and applicability.

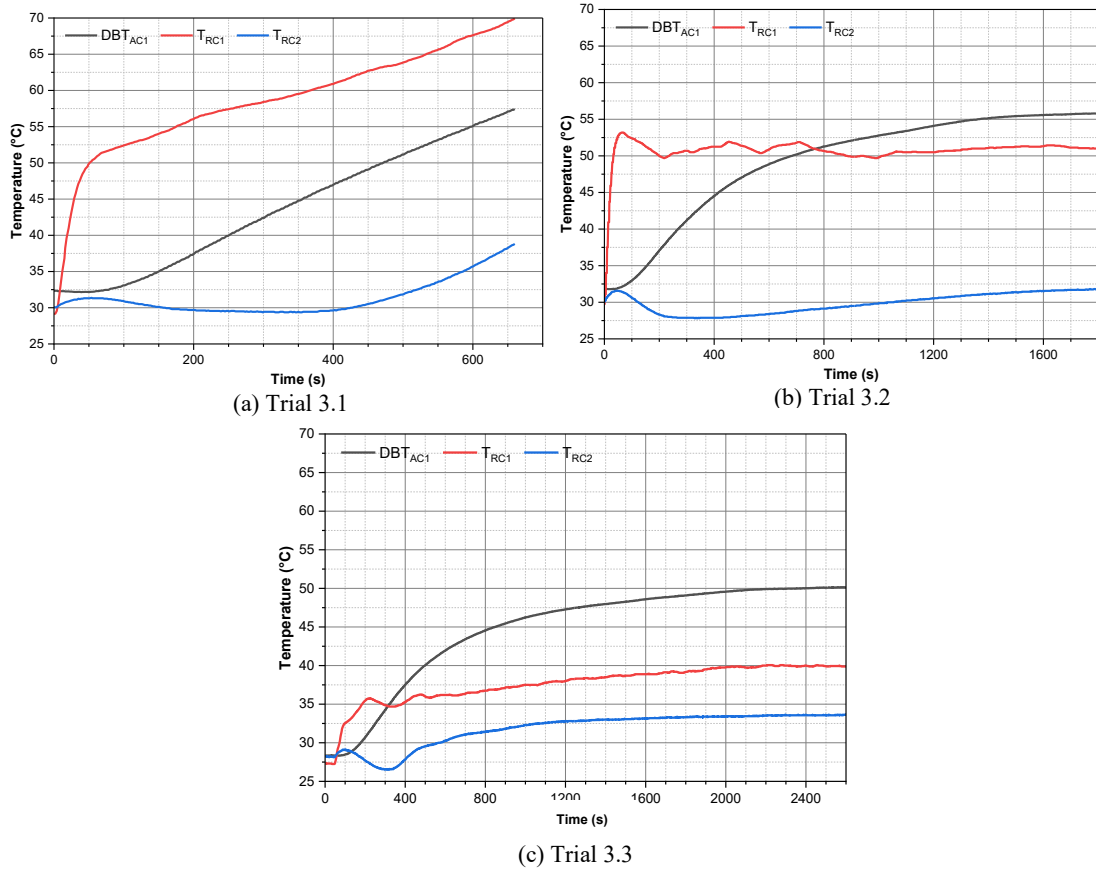


Figure 5. Changes over time of DBT_{AC1} , T_{RC1} , and T_{RC2} in Trial 3.x

Trial 3.x was conducted with the addition of EH to increase DBT_{AC1} . The results of Trial 3.x are shown in Figure 5.

In Trial 3.1, with the same fan's MV values as Trial 2.1 (which did not reach equilibrium), adding EH to the drying airflow made it even more impossible to achieve a steady state. This change can be explained by the following thermal balance equations.

The thermal balance in the refrigerant cycle still follows Equation 1. However, with the addition of EH, Equation 2 is modified to:

$$Q_{EVA} - Q_{COND-2} - Q_{EH} = 0 \quad (4)$$

Consequently,

$$W_{\text{COMP}} + Q_{\text{EH}} = Q_{\text{COND-1}} \quad (5)$$

Equation 5 shows that the heat released to the environment from COND-1 includes both COMP's power consumption and the heat supplied by EH. Therefore, adding EH further increases the excess heat, requiring COND-1 to release even more heat to the environment.

After Trial 3.2, the system achieved thermal equilibrium at 56 °C for DBT_{AC1}, 51 °C for T_{RC1}, and 33 °C for T_{RC2}. In Trial 3.3, due to a higher heat release level, the equilibrium points were observed to be lower, with DBT_{AC1}, T_{RC1}, and T_{RC2} values of 50, 40, and 33 °C, respectively. The results show that when the appropriate MV_{F-1} is selected to dissipate excess heat, the system can still reach a stable state despite the added heat from the electric heater. At the same time, the drying airflow's temperature is increased, expanding the system's application potential.

4. CONCLUSION

Traditional drying methods are energy-intensive, creating challenges for efficiency and sustainability. Heat pump drying (HPD) offers a promising alternative by improving energy efficiency through integrated heating and cooling. Repurposing components from discarded air conditioners and refrigerators for HPD systems can also reduce e-waste, lower production costs, and support environmental sustainability. Three no-load experiments assessed HPD system stability and thermal equilibrium under various conditions, including with and without a sub-condenser for excess heat release and with and without an electric heater as an additional heat source.

Key findings from Trial 1.x, Trial 2.x, and Trial 3.x include:

Sub-condenser as a critical component: COND-1 is essential for maintaining system stability and operational safety because it can release heat accumulation caused by COMP and EH to the surroundings.

Supplementary heat necessity: Without EH, DBT_{AC1} only reached 37 - 44 °C, insufficient for many drying applications. Therefore, adding an electric heater is crucial to enhance system efficiency and broaden its applicability.

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