Performance evaluation of R-1234yf as alternative to R-22 for date fruit drying machine

Hifni Mukhtar Ariyadi[1*], *Yurian* Ariandi Andrameda[1], *Ardi* Jati Nugroho Putro[1], *Dhanang* Sulistio Aji[1], and *Nyayu* Aisyah[2]

[1]Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika No.2, Yogyakarta, Indonesia
[2]Department of Mechanical Engineering, Vocational School, Universitas Gadjah Mada, Jl. Yacaranda, Sekip Unit IV, Yogyakarta, Indonesia

Abstract. Heat pump drying in the food industry is notable for its efficiency and energy savings. When designing a date fruit drying machine, it is crucial to consider heat transfer characteristics and performance, measured by parameters such as the coefficient of performance (COP), specific energy consumption (SEC), and specific moisture extraction rate (SMER). This study compares the performance of R-22 and R-1234yf in terms of energy efficiency and drying capacity for a date drying machine operating at a drying temperature of 60°C to dry 20 kg of dates per hour, under environmental conditions of 26°C. Results show that the machine the COP using R-1234yf is 3.449, slightly lower than R-22's COP of 3.894, indicating that R-22 is more energy efficient. The specific energy consumption (SEC) with R-1234yf is 0.014 kWh/kg, compared to R-22's 0.013 kWh/kg, while the specific moisture extraction rate (SMER) for R-22 is 75.216 kg/kWh, higher than that of R-1234yf at 69.614 kg/kWh. These findings suggest that although R-22 has superior efficiency, R-1234yf provides a competitive alternative, especially considering its significantly lower global warming potential (GWP). Thus, R-1234yf is a practical and environmentally friendly choice for date drying applications, supporting the transition towards more sustainable refrigerant options.

1 Introduction

Heating drying systems are used to remove moisture from various materials, such as food, wood, and textiles. There are different types of heating drying systems, including solar-assisted heat pump drying systems, resistance heating apparatus-cum-solar drying systems, and ohmic heating with convective drying systems 1. These systems use different methods to generate heat, such as solar energy, electric resistance, and microwave tomography 2. Overall, heating drying systems use different methods to generate heat and remove moisture from materials. The choice of system depends on the type of material being dried and the desired drying rate.

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*Corresponding author: hifni.m.a@ugm.ac.id

The use of heat pump drying in the food industry has gained significant attention due to its efficiency and potential for energy savings. Heat pump dryers have proven to be a valuable tool in drying various food products, ensuring high quality and reduced drying times. Heat pump dryers offer numerous advantages over conventional hot-air dryers. One key advantage is their higher energy efficiency. According to various studies, the drying efficiency of heat pump dryers typically ranges between 80 and 90%, significantly surpassing that of conventional dryers. This increased efficiency translates into substantial energy savings, making heat pump dryers a sustainable alternative 3 .

In recent years, there has been a considerable amount of research and development in the field of heat pump drying systems. One promising advancement in this area is the heat pump dehumidifier dryer, which has proven to be more efficient and effective than traditional hot-air dryers for the drying in food industry 4.

Heat pump dehumidifier dryers offer a range of advantages over conventional dryers. Firstly, their energy efficiency is significantly higher. This is due to the fact that heat pump dehumidifier dryers work by extracting heat from the surrounding air and using it to evaporate moisture from the food products 5. The heat is then recycled back into the system, resulting in lower energy consumption. This not only reduces operating costs but also minimizes the environmental impact by decreasing the release of gasses into the atmosphere. Furthermore, heat pump dehumidifier dryers can operate independently of outside ambient weather conditions. This means that they can maintain a consistent drying environment regardless of external factors such as humidity or temperature fluctuations. This is particularly advantageous for the drying of delicate food products that require precise conditions to maintain their quality 6.

The process of drying dates fruits has gained significant attention in recent years. One method that offers numerous advantages is heat pump drying. Heat pump dryers, widely used in industries such as timber and food drying since the 1970s, have demonstrated high energy efficiency compared to conventional air-drying methods. For instance, when it comes to wood drying, heat pump dryers can save up to 45% and 42% more primary energy than hot air dryers fueled by coal or gas 6. Extensive research has been conducted on the utilization of heat pump systems for fruit drying purposes. Heat pump dehumidifier dryers present several benefits over traditional hot-air dryers, including improved energy efficiency, enhanced product quality, and the ability to operate independently regardless of outside ambient weather conditions 7.

Refrigerants play a significant role in the heat pump systems, yet they significantly impact the environment, particularly through their contribution to global warming and ozone depletion. Chlorodifluoromethane (R-22) has historically been one of the most widely used refrigerants, has good thermodynamic properties for many applications including in heat pump system. However, R-22 refrigerant is being phased out due to its harmful effects on the environment with a high Global Warming Potential (GWP) which is about 1810. Thus, It is recommended to switch to more environmentally friendly refrigerants 13 in response to mounting concerns about global warming and ozone depletion 8.

Thus, the search for alternative refrigerants that minimize environmental damage has gaining attention 910. Tetrafluoro propene (R-1234yf), is a hydrofluoroolefin (HFO) refrigerant that becomes one of the promising replacements for R-22. It has a GWP of less than 1, making it substantially less harmful to the environment compared to R-22. In terms of environmental impact, R-1234yf offers a significant advantage due to its negligible contribution to global warming, allowing industries such as food drying to align with global sustainability goals. The use of R-1234yf supports the reduction of greenhouse gas emissions, which is essential in the transition toward environmentally friendly and sustainable technologies.

This study aims to evaluate the performance of R-1234yf as a green and sustainable replacement for R-22 in a heat pump-driven date drying machine. The objective is to analyze key performance metrics—namely, the coefficient of performance (COP), specific energy consumption (SEC), and specific moisture extraction rate (SMER)—to assess the feasibility of R-1234yf as an alternative refrigerant that minimizes environmental impact while maintaining acceptable drying efficiency. This analysis will provide insights into the trade-offs between energy efficiency and sustainability in the context of food drying applications.

2 Methodology

2.1 Refrigerant Characteristic

While choosing and using refrigerants, variables including flammability, ozone depletion potential (ODP), and global warming potential (GWP) have been consistently tracked. To solve them and raise the general effectiveness of air conditioning technology, it is essential to comprehend these problems. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which deplete the ozone layer, were once often used in refrigeration systems 11, while CFCs were totally phased out in 2010 12.

Refrigerant R-1234yf is a low global warming potential (GWP) substitute for R-22, which is currently used in refrigeration systems. It is being widely studied as a potential alternative to R-22 due to its environmental benefits and other benefits like Heat transfer coefficient, Performance evaluation, better coefficient of performance (COP), Compressor efficiency 14. Table 1 shows some differences in the properties of refrigerant R-22 and R-1234yf.

Table 1. Properties of refrigerant R-22 and R-1234yf. 1415

Properties	R-22	R-1234yf
Chemical Formula	$CHCLF_2$ (Chlorodifluoromethane)	$CH_2=CFC_3$ (2,3,3,3-tetrafluoropropene)
Critical Temperature (°C)	96.10	94.70
Critical Pressure (bar)	49.90	33.82
Normal Boiling Temperature (°C)	-40.8	-29.49
ODP	0.055	0
GWP	1600	4
ASHRAE Safety Class	A1 (low toxic dan Non-Flammable)	A2L (low toxic dan Low Flammable)

2.2 System Description

The date drying machine uses a heat pump to extract heat from the ambient. The heat pump utilizes a refrigerant that undergoes a continuous process of compression, condensation, expansion, and evaporation so that the heat displacement from the condenser can occur in the dryer room and allows for the drying process as illustrated in the Fig. 1. The refrigerant is compressed in the compressor by increasing the pressure. The vapor entering the compressor is saturated vapor at lower pressure (point 1) and the vapor coming out of the compressor is superheated vapor at higher pressure (point 2). The high-temperature vapor flows into the condenser. In the condenser there is a heat transfer process, where the heat released enters the dryer room. The heat transfer is assisted by a fan and causes a significant increase in temperature in the dryer room. As a result of heat transfer, the vapor temperature decreases and condenses into a high-pressure saturated liquid (point 3). The liquid then flows into the expansion valve and experiences a drastic decrease in pressure and temperature so that it

returns to a low-pressure 2-phase fluid (point 4). The fluid then flows into the evaporator where the evaporation process occurs by absorbing the ambient heat to convert the liquid back to saturated vapor (point 1).
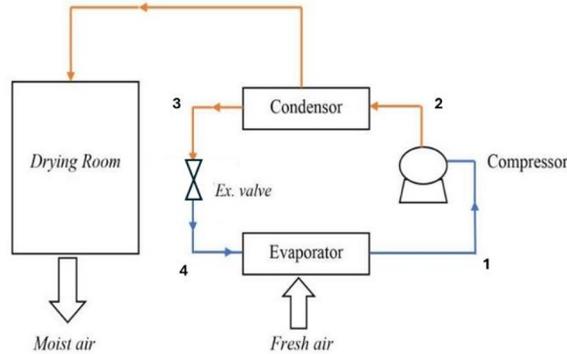

Fig 1. Working cycle of date dryer machine

As seen in Fig. 1, the objective of this drying is to maintain a hot temperature in the drying room of 60 °C to dry 20 kg of dates in one drying process per hour. This goal must be achieved under environmental conditions of 26 °C. This study uses several conditions such as the refrigerant used is R-22 and R-1234yf, the condenser temperature is set at 70 °C, the evaporator temperature is set at 16 °C. The compressor isentropic efficiency assumed to be 80%, and fan power in drying room is 100-Watt, air humidity is ignored, and there are no system leaks or pressure drops.

2.3 Numerical Situation

The following assumptions are used in the calculation of cycle performance to simplify the calculation process:

a. No system leaks and pressure drop: In the dryer system components such as condensers, evaporators, compressors, and expansion valves are assumed not to experience system leaks or pressure drops.

b. No heat transfer resistance: The heat transfer process is assumed to have no resistance from the evaporator or condenser walls. This assumption facilitates the calculation process because the heat transfer process works perfectly.

c. Working system in a stable state: In the calculation of the refrigerant work system is assumed to be in a stable state, meaning that in the work cycle there are no variations in temperature, pressure, or other parameters that cause significant changes. For the sake of simplicity of calculation, start-up and shutdown are ignored.

d. Compressor efficiency is 80 percent: The compressor used has a power of 1 HP and is assumed to have an efficiency of 80 percent with a power factor of 0.8 in single phase.

e. Expansion valve is isenthalpic: Certain calculations assume that the process in the expansion valve is isenthalpic. The process assumes that the phase change occurs without any loss of initial liquid mass. While this assumption also simplifies the calculation, it does not use actual expansion.

The drying load (Q_{load}, kJ) in this calculation is the total heat required during the drying process and is obtained as in Eq. (1).

$$Q_{load} = m_{dates} \cdot Cp_{dates} \cdot \Delta T \qquad (1)$$

The heat transfer rate ($\dot{Q}$, kW) involves releasing heat to the drying room and absorbing heat from the environment by the refrigerant during the drying cycle as in Eq. (2).

$$\dot{Q} = \dot{m}_{ref} \cdot \Delta h \tag{2}$$

Determination of the refrigerant mass flow rate must be done before designing the date dryer. Eq. (3) can be used to determine the refrigerant mass flow rate required to dry dates.

$$\dot{m} = \rho \cdot \dot{V} \tag{3}$$

The drying rate ($\dot{m}_d$, kg/s) can be calculated by comparing the total water content being evaporated ($m_{d,in} - m_{d,out}$, kg)) with the time taken for the drying process (t, s). Eq. (4) can be used to calculate the drying rate of the date drying machine.

$$\dot{m}_d = \frac{m_{d,in} - m_{d,out}}{t} \tag{4}$$

The work of the compressor needs to be determined so that the drying system can work optimally. Eq. (5) used to calculate the compressor work.

$$\dot{W}_{comp} = h_2 - h_1 \tag{5}$$

Compressor efficiency can be calculated by comparing the enthalpy at first and second compression of the refrigerant. Eq. (6) can be used to calculate compressor efficiency.

$$Eff_{comp} = \frac{h_{2,is} - h_1}{h_2 - h_1} \tag{6}$$

The actual value of the compressor can also be calculated by Eq. (7), using parameters such as electrical voltage, electrical power, and electrical power constant.

$$\dot{W}_{act,comp} = V . I . \eta . Cos \tag{7}$$

After getting the actual work of the compressor we can calculate the refrigerant flow rate by dividing it by the sum of the enthalpy. Eq. (8) can explain the calculation.

$$\dot{m}_{ref} = \frac{\dot{W}_{act,comp}}{h_2 - h_1} \tag{8}$$

After calculating the drying load required by the date drying machine and knowing the compressor work. Calculate the Coefficient of Performance (COP) on the date drying machine. COP can be calculated by comparing the dryer load with the compressor work. COP can be explained by Eq. (9).

$$COP_{dryer} = \frac{\dot{Q}_{cond}}{\dot{W}_{comp}} \tag{9}$$

Specific Moisture Extraction Rate (SMER) is a calculation of the working efficiency of the drying machine in removing moisture content in dates. The calculation includes how much water content is removed per watt (electrical power used). The equation used to explain SMER is as in Eq. (10).

$$SMER = \frac{\dot{m}_d}{\dot{W}_{comp} + \dot{W}_{fan}} \qquad (10)$$

In this calculation, Specific Energy Consumption (SEC) is the calculation of the amount of energy required to dry dates. SEC can be calculated in units or in kilograms depending on the parameters used. Eq. (11) can explain the SEC calculation used in the dryer of date fruit.

$$SEC = \frac{1}{SMER} \qquad (11)$$

3 Result and Discussions

R-22 and R-1234yf were analysed using numerical analysis to compare each other. In condenser was set at 60 °C and evaporator was set at 16 °C for both refrigerants. In order to enhance heat transfer in the condenser, the refrigerant temperature must be greater than the air temperature. This requirement guided the temperature choice. Similar to this, in order to facilitate heat transfer in the evaporator, the refrigerant temperature had to be lower than the air temperature in the cold storage. To understand performances, R-22 and R-1234yf, work cycle, temperature, COP performances in condenser and evaporator and drying efficiency were being evaluated.

3.1 Cycle Performance

Fig. 2 presents work cycle plots on temperature-entropy (T-s) diagrams for two refrigerants: (a) R-22 and (b) R-1234yf.
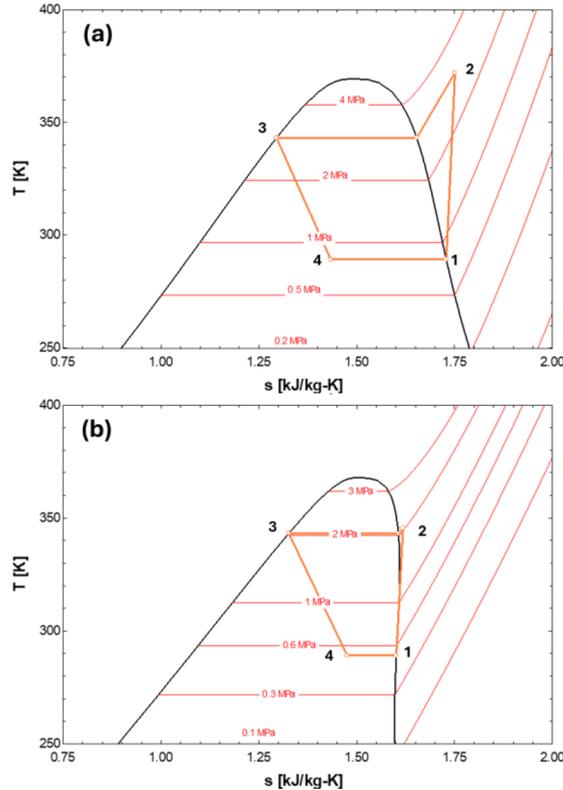

Fig 2. Work cycle plot on temperature and entropy diagram. (a) R-22 and (b) R-1234yf

Fig. 2(a) shows the work cycle graph based on the temperature-entropy (*T-s*) diagram. The figures have similarities in the temperatures in the evaporator and condenser but still both have differences in the process pressure where the R-22 has a process pressure at low pressure of 8.13 bar and high pressure of 29.98 bar. So that from this case there is an interval of about 17 bar carried out by the compressor to increase the temperature in the R-22 system, although after this pressure increase there is a high temperature increase of around 91.2°C. At point 1, it hits the saturated vapor point and rises to point 2 with superheated vapor conditions. and drops based on the pressure line which hits the saturated liquid line at point 3 and drops to point 4 where an isenthalpic event occurs.

Fig. 2(b) shows the temperature-entropy diagram graph for R-1234yf which shows that if this refrigerant point one is in the superheated vapor area, it does not fit on the saturated vapor line like refrigerant R-22. this adjusts to the conditions in the system parameters. R-1234yf has lower pressure at 5.26 bar with the same conditions and increases after the pressure compression process to 34.32 bar. Therefore, from this there is an interval increase of about 29 bar, this lower interval indicates that the compressor performance will be higher but the temperature rise after passing through the compressor is 70°C, lower than that of R-22 which is 91.2°C.

The size comparison on the pressure enthalpy graph on the work cycle using R-22 and R-1234yf can be seen in Fig. 3. It shows that the R-22 refrigerant has a larger area, and its position is higher than the R-1234yf refrigerant, indicates that R-22 has a greater COP for this process.
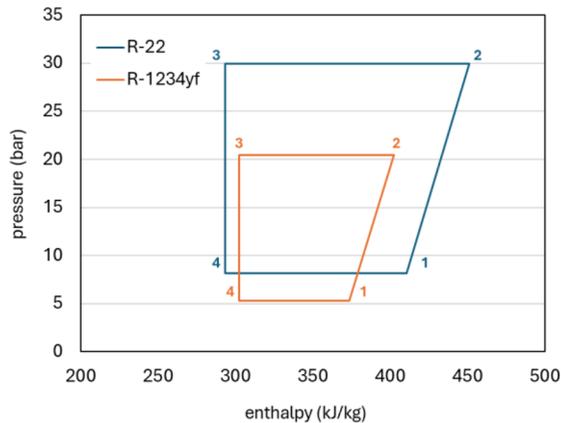

Fig.3. Pressure and enthalpy diagram for R-22 and R-1234yf

3.2 Energy and Performance Evaluation

The performance analysis of refrigerants R-1234yf and R-22, summarized in Table 2, highlights key differences in thermodynamic efficiency and energy consumption, which have significant implications for dates drying applications. The coefficient of performance (COP), a measure of energy efficiency, is slightly lower for R-1234yf (3.449) compared to R-22 (3.894), indicating that R-1234yf can provide cooling per unit of energy input. It is noteworthy that the COP of R-1234yf is still competitive with that of R-22, demonstrating that R-1234yf can offer a viable alternative in systems designed for high energy efficiency, especially considering its lower environmental impact.

The mass flow rate ($\dot{m}_{ref}$) for R-1234yf (0.00645 kg/s) is significantly greater than that of R-22 (0.004096 kg/s), suggesting that more R-1234yf is required to achieve a similar

cooling effect. This can be attributed to the lower latent heat of vaporization of R-1234yf, which necessitates a higher quantity of refrigerant to maintain comparable performance. Despite both systems having identical heat production rates (Q_{cond}) of 0.646 kW, the work input required by the compressor ($\dot{W}_{comp}$) is higher for R-1234yf (0.1873 kW) compared to R-22 (0.1659 kW), contributing to the lower efficiency of R-1234yf.

Table 2. Energy and performance results of R-22 and R-1234yf refrigerant

Parameter	Unit	Value	
Refrigerant	-	R-1234yf	R-22
COP	-	3.449	3.894
$\dot{m}_{ref}$	kg/s	0.00645	0.004096
$\dot{Q}_{cond}$	kW	0.646	0.646
$\dot{Q}_{evap}$	kW	0.4587	0.4801
$\dot{W}_{comp}$	kW	0.1873	0.1659
SMER	kg/kWh	69.61364	75.21625
SEC	kWh/kg	0.014365	0.013295

In addition to COP, the system performance is also analyzed based on the specific moisture extraction rate (SMER) and specific energy consumption (SEC). The SMER, which measures the amount of moisture removed per unit of energy, favors R-22, with a value of 75.21625 kg/kWh versus 69.61364 kg/kWh for R-1234yf. This suggests that R-22 is more effective in dehumidification applications. Similarly, the SEC of R-1234yf (0.014365 kWh/kg) is higher than that of R-22 (0.013295 kWh/kg), indicating that R-1234yf requires more energy per kilogram of refrigerant processed.

From the results, it is shown R-1234yf offers a much more environmentally friendly alternative, with a significantly lower GWP and no ODP, making it a promising green replacement for R-22. Although R-1234yf shows a slight reduction in thermodynamic efficiency, with lower COP, SMER, and higher SEC compared to R-22, its performance is still competitive, especially when considering the environmental advantages. The mass flow rate and compressor work requirements of R-1234yf are higher, which may impact system design and operational costs; however, its reduced environmental footprint makes it a viable and sustainable choice for refrigeration systems looking to transition away from R-22. Thus, R-1234yf represents a balanced solution that allows for a significant reduction in environmental impact while maintaining acceptable performance levels, supporting the shift towards greener refrigerant technologies.

4 Conclusion

The comparative performance analysis of refrigerants R-1234yf and R-22 reveals that while R-22 offers higher thermodynamic efficiency, R-1234yf provides an environmentally sustainable alternative with a significantly lower global warming potential (GWP) and no ozone depletion potential (ODP). R-22 demonstrates superior values in terms of coefficient of performance (COP), specific moisture extraction rate (SMER), and specific energy consumption (SEC), with a COP of 3.894 compared to 3.449 for R-1234yf. Similarly, the SMER of R-22 (75.216 kg/kWh) is higher than that of R-1234yf (69.614 kg/kWh), indicating greater dehumidification efficiency. The specific energy consumption (SEC) for R-1234yf is

also higher (0.014365 kWh/kg) than that of R-22 (0.013295 kWh/kg). Despite the performance advantages of R-22, its high environmental impact necessitates a shift towards more sustainable alternatives. R-1234yf, with its lower GWP and zero ODP, remains competitive and represents a viable green replacement for R-22, offering a practical compromise between efficiency and environmental considerations.

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