THERMAL PERFORMANCE AND ECONOMIC ANALYSIS OF THE HEAT PUMP DRYER

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ABSTRACT

This work presents the thermal performance and economic perspectives of a high temperature heat pump dryer. The optimal design under the thermodynamic and computational fluid dynamics (CFD) methods are used to develop the prototype heat pump system. A drying chamber of 0.94 m^3 is supplied heat by a 3.2 kW R-134a heat pump. Gymnema tea is used to evaluate the thermal performance at a drying temperature of 45-60 ^{o}C. The optimal data are found under the testing conditions of an operating time of 240 minutes, a moisture content of 60% Wet-basis, a drying rate of 1.20 $k_{gw}/(kg_G \cdot min)$, and a specific consumption of 3.71 kWh/kg_G. Drying efficiency, energy efficiency ratio (EER), and heating coefficient of performance (COP_H) are approximately 71.56%, 2.42 kW_{th}/kW_e, and 5.37 respectively. Economic results are a payback period of 1.02 years and an internal rate return of 49.9%.

KEYWORDS: Gymnema tea, Coefficient of performance, Drying efficiency, Payback period

1. Introduction

Gymnema is a common ingredient in the northern area, Thailand cuisine as the local vegetable and commercial herb tea. Traditional products are used to prevent diabetics [1, 2]. Many drying techniques are used to dry Gymnema such as solar drying process under a dying time of 1-2 days. This process reveals disadvantage point as a long operating period, a limit-potential of solar energy, and a climate of the northern area. From above results, an active drying method is presented in commercial product. Heater hot-air over and vapor compression heat pump as directly driven from electrical power are represented in present. In this work, a high temperature heat pump at the range of 40-70 °C for drying Gymnema is developed to handle the high quality vegetable and price products [3].

Natural antioxidants, color, quality, and consumer acceptance [4-6] are productivity from the expected drying products. Heat pump drying system is a common method for removing moisture, microbial spoilage, and chemical reactions [7]. Heat pump technique was reported by various works such Singh et al [8], who evaluated the suitable drying conditions in terms of the humidity and temperature sensitive values. Mohanraja et al [9] and Tunckal and Doymaz [10] showed energy saving from exhaust heat recovery unit. The integrated systems between heat pump and other technologies in drying process were implemented by Cheng et al. [11] and Cranston et al [12]. Binnisha et al [13] presented a compound parabolic solar dryer to extract moisture from a material of 74% Dry-basis to be a final moisture 7% Dry-basis. Drying time and drying ratio were approximately 12 h and 3.5, respectively. Sanpang [14] focused on a drying kaffir lime leaves from a hybrid heater-heat pump system. The dried kaffir lime leaves revealed the best color at a hot air temperature of 45-55 °C. Seanmeema et al [15] studied a curcumin-heat pump dryer. An initial moisture content of approximately moisture content of 525-565% Dry-basis was extracted to a final moisture content of 10% Dry-basis. Three step temperatures of 45 °C, 50 °C, and 55 °C are designed as drying performance at a velocity of 0.5 m/s. Coefficient of performance (COP) was found at the range of 2.149-2.919. Chunkaew [16] reported a banana slide of 400 g at an initial moisture content of 281% Dry-basis, which was dried to a low moisture content of 6.24% Dry-basis. The COP values were found in the range of 3.32-4.24. Saengsuwan [17] analyzed chrysanthemum flowers to reduce a product moisture lower than 5%. An optimum temperature of 65 °C was reported under a testing time of 8 h and a power consumption 1.091 kWh/h. Auprakul et al [18] focused water hyacinth by a R-22 heat pump dryer. Three temperature levels of 40 °C, 50 °C, and 60 °C were conducted for the drying periods of 4 h, 5 h, and 6 h, respectively. The COP results were 5.25, 4.88, and 4.51, respectively. Aktas et al [19] studied a heat pump mint leaves dryer. The dryer—air heat recovery unit, air source, heat pump system, and proportional temperature controller—were developed. The experiment results were performed at a velocity of 2 m/s, 2.5 m/s, and 3 m/s under the ambient temperature of 35 °C and a COP of 4.06.

As mentioned above, many works reported the analyzing of vegetable drying process. Various types of vegetables used the heat pump system to reduce humidity. The correlation conditions of drying chamber volume, temperature, air pressure drop, velocity, air ventilation, humidity, moisture content, and power consumption are not investigated on an optimal heat pump dryer. Thus, in this work an optimal design based on thermodynamics, computational fluid dynamics (CFD), energy consumption, drying time, and economic perspectives is implemented. The objective of this study are as follows:

1) To develop a high-temperature heat pump dryer for hot air temperature of 40-70 °C.

2) To optimize the suitable drying conditions under the thermodynamic, CFD, energy consumption, drying time, and economic impacts.

3) To evaluate the drying curve of Gymnema tea.

2. System description

A schematic diagram of the heat pump drying chamber is depicted in Figure 1 (a). The ambient air at points 1-2 is used as heat source of an R-134a vapor compression heat pump cycle. Heat transfer process between the ambient air and refrigerant is conducted at an evaporator, as presented in Figure 1 (b). Working substance at a low-temperature boils at a low-pressure into vapor at point 1H. A compressor is used to increase the vapor working fluid temperature and pressure at point 2H. A super heat vapor rejects heat at a condenser by using the moist air in a drying chamber at point 3. Working fluid is consolidated to be a liquid phase at point 3H. At the same time, hot air is boosted to a high-level heat of approximately 60-70 °C at point 4. A hot air blower is used to circulate hot air with a low-relative humidity (RH, %) through drying material. A high-humidity air at point 5 is rejected by an intake air vent at point 6. At the same time, the fresh air is conducted by a ventilation fan to reduce the relative humidity of drying air at point 7. The liquid working fluid at point 3H is depressurized by an expansion valve at point 4H, and the new vapor compression cycle is restarted. A R-134a heat pump prototype is visualized in Figure 1 (c).

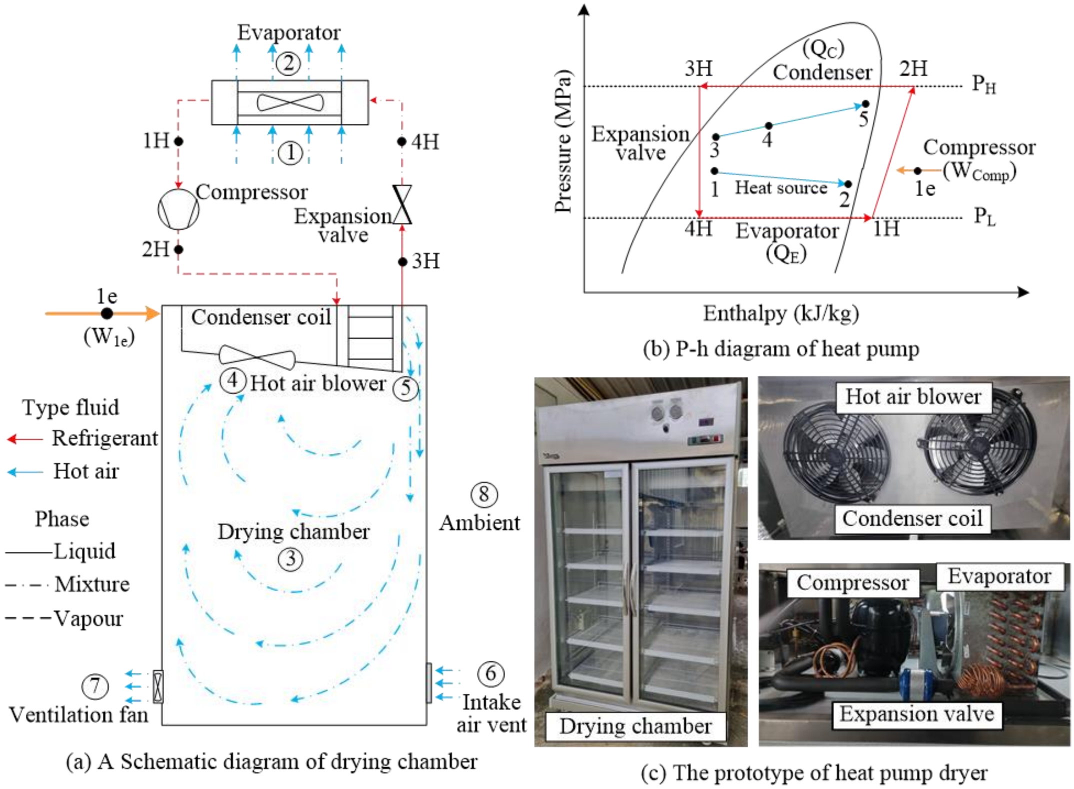

Figure 1 Heat pump dryer

3. Materials and methods

3.1 CFD analysis

The CFD method is used to simulate the optimal parameters of velocity, pressure, and temperature, as specified in Table 1. The velocity of the air directly affects heat transfer and the evaporation of moisture from the drying object. The pressure inside the dryer may influence the rate of moisture evaporation, while temperature is a critical factor in controlling the evaporation rate of moisture from the material being dried. The heat pump system—R134a refrigerant, 0.746 kW compressor, 2.75 kW evaporator, 3.2 kW condenser, and 1 TR expansion valve—are implemented. The drying chamber is designed at a 1.10 m-width, 0.58 m-deep, 1.47 m-height, and 0.94 m^3-volume.

Table 1 **Input parameters for the CFD simulation.**

Parameter	Input value	Unit
Fluid	Air	-
Heat source	70	°C
Volume flow rate	0.068	m^3/s
Pressure openings	Environment pressure	-
Outlet velocity	2.5	m/s
Maximum gap size	0.00135	m

3.2 Drying test

Drying material is a Gymnema of 2 kg at a size of 5 mm. Dry bulb temperature, relative humidity, velocity, mass, and power consumption are continuously measured. Temperature and relative humidity sensors are the Tenmars TM305U Humidity Datalogger at a temperature range of -40 °C to 85 °C and a relative humidity range of 1-99% under an accuracy of ±0.61 °C and ±0.58%, respectively. The power logger is the TEKON550 power analyzer at the operation range of 0.016-600 kW and an accuracy of ±0.9%. The drying conditions of 45 °C for 240 minutes, 55 °C for 60 minutes, and 60 °C for 30 minutes are designed for Gymnema tea.

3.3 Thermal performance of heat pump dryer

Thermal performance of the heat pump dryer is presented in terms of the specific moisture extraction rate (SMER, g_w/kWh), heating coefficient of performance (COP_H), drying efficiency (η_{Dry}, %), energy efficiency ratio (EER_{Dry}, kW_{th}/kW_e), and specific energy consumption (SEC, kWh/kg_G), as presented in Figure 2.

3.4 Economic analysis

Economic analysis of the heat pump dryer for Gymnema tea focuses on the payback period (PB, y), net present value (NPV, USD), and internal rate of return (IRR, %). Mathematical correlation is represented in Figure 2. Initials parameters for economic analysis are summarized in Table 2.

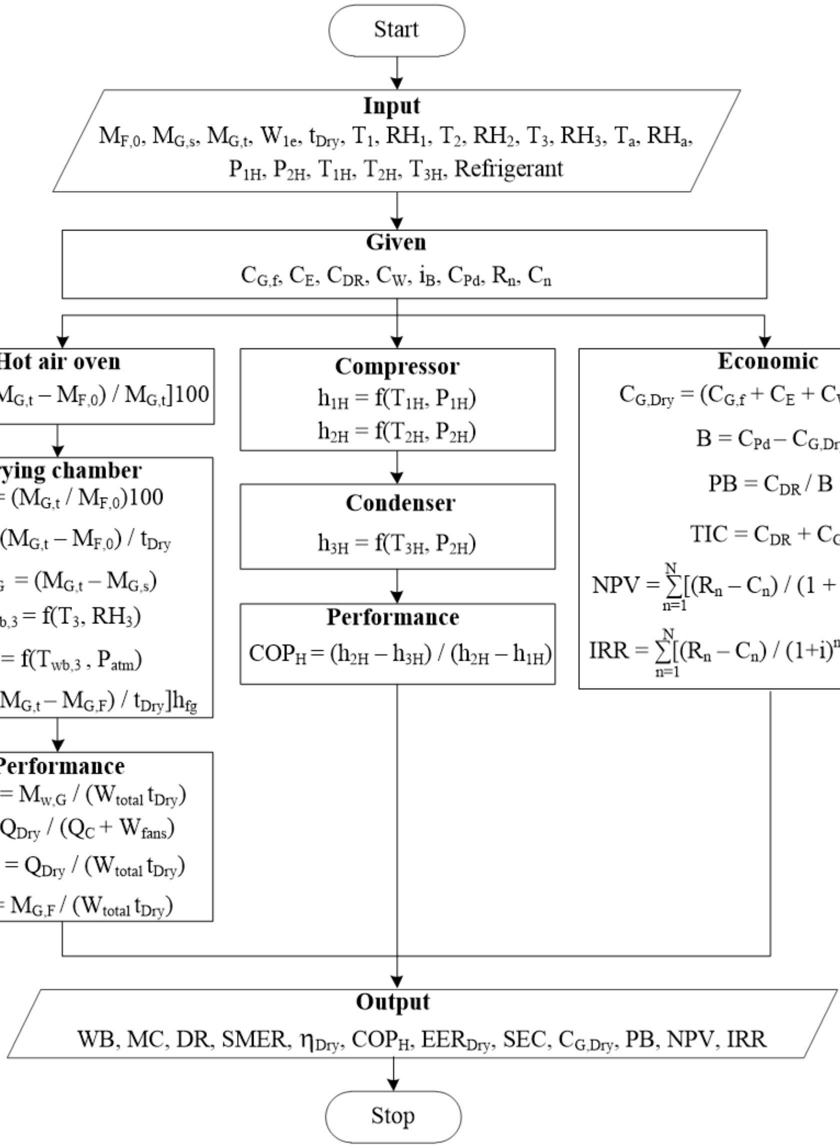

Figure 2 A mathematical model of the drying chamber

Table 2 Initials parameters of economic analysis

Parameters	Value	Unit
Cost of heat pump dryer system (C_{DR})	2,789	USD
Cost of fresh Gymnema ($C_{G,f}$)	1.40	USD/kg
Cost of electricity (C_E)	0.132	USD/kWh
Cost of wage (C_w)	8.39	USD/d
Cost of maintenance (C_m)	279.80	USD/y
Mass of fresh Gymnema ($M_{G,F}$)	400	kg/y
Mass of dried Gymnema ($M_{G,d}$)	96	kg/y
Cost of dried Gymnema (C_{Pd})	55.96	USD/kg
Number of operation days per year (D)	200	d
Discount rate (i)	7.05	%
Life of dryer system (Y)	10	y

4. Results and discussion

4.1 CFD

The CFD simulation of the drying process is presented in Figure 3. The fluid dynamics shows a regular ventilation performance of five drying material shelves. A wind speed of 1.28 m/s, an air pressure of 101,324.56 Pa, and a hot air temperature of 58.77 ^{o}C are the average values under a steady state performance. Double drying blowers with each power of 19 W and a diameter size of 9 inch are selected from the CFD results. A ventilation fan of 10 W and a diameter size of 4 inch is selected to reduce the humidity of drying air for 5 shelves and 10 inch intake air vent.

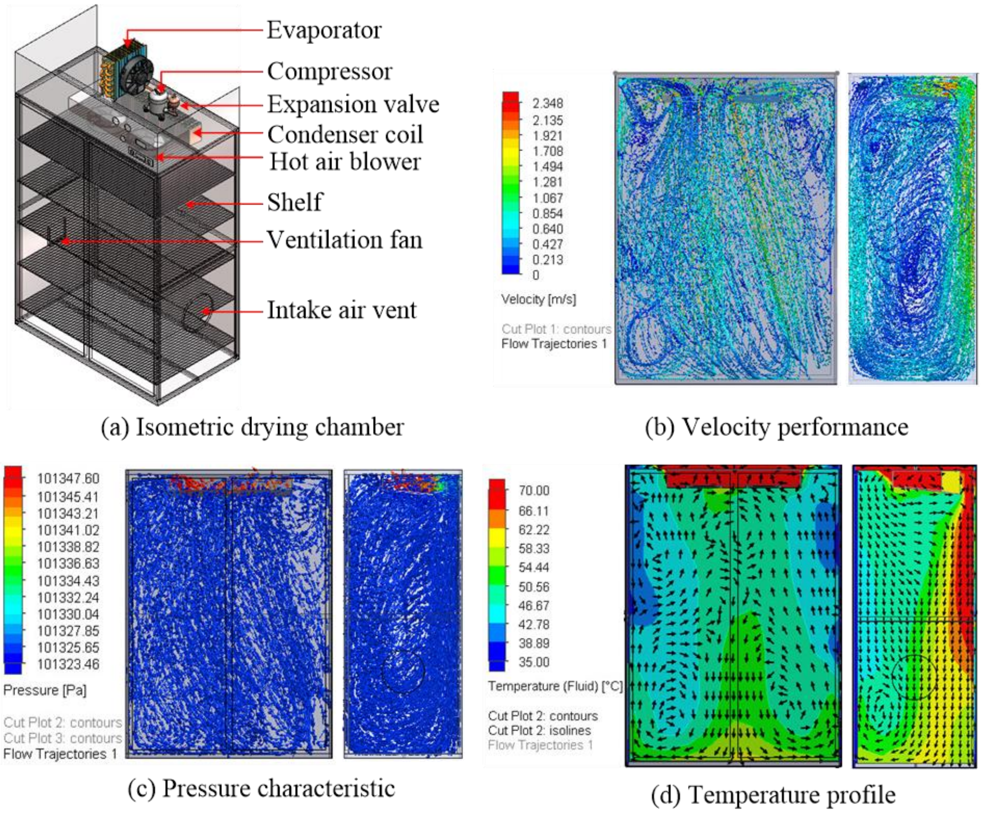

Figure 3 Computational fluid dynamics of drying process

4.2 Thermal performance

Figure 4 displays the moisture, relative humidity, and temperature data in the drying chamber. Gymnema reveals an initial moisture of 84.50% Wet-basis. The moist air property at a temperature of 27.37 ^{o}C and a relative humidity of 90.2% transfers heat from the heat pump system. A testing time of 330 minutes is continuously operated with the final drying condition of hot air cycle is a hot air temperature of 60 ^{o}C, a relative humidity of 27.67%, and a moisture content of 1.00% Wet-basis. The best dried Gymnema product reveals at an operation time of 240 minutes for a moisture content of 22.50% Wet-basis, a hot air temperature 45 ^{o}C, and a relative humidity of 41.00%. This output Gymnema product will be sent to the roast process at a temperature of 80 ^{o}C. An essential oil readily volatile of approximately 8.89% Wet-basis and the best aroma tea are found at these drying conditions. The mold and musty odor are the main reasons for the low-moisture content material, which corresponds with Dmowski and Ruszkowska [20] at a lower than 9%.

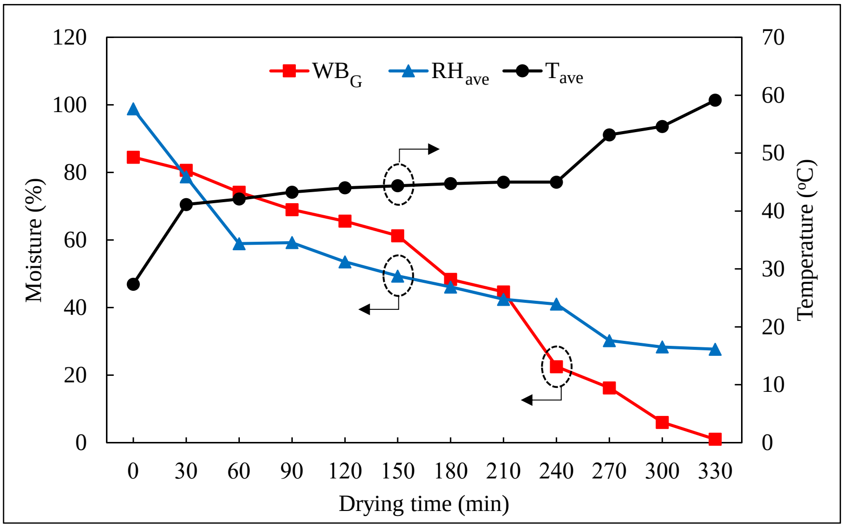

Figure 4 **Moisture, relative humidity, and temperature of the drying process**

Figure 5 shows the correlation between the moisture content based on the dry-basis standard and drying rate parameters. A moisture content of 676% Dry-basis is sharply increased into a preheat period of 30 minutes at a high-drying rate of 8.72 $kg_w/(kg_G \cdot min)$. In a constant drying rate period of 30-150 minutes, a drying rate of 5.52 $kg_w/(kg_G \cdot min)$ reveals to extract moisture out of the surface of drying materials. In a falling drying rate period of 120-330 minutes illustrates a low-drying rate of 1.45 $kg_w/(kg_G \cdot min)$.

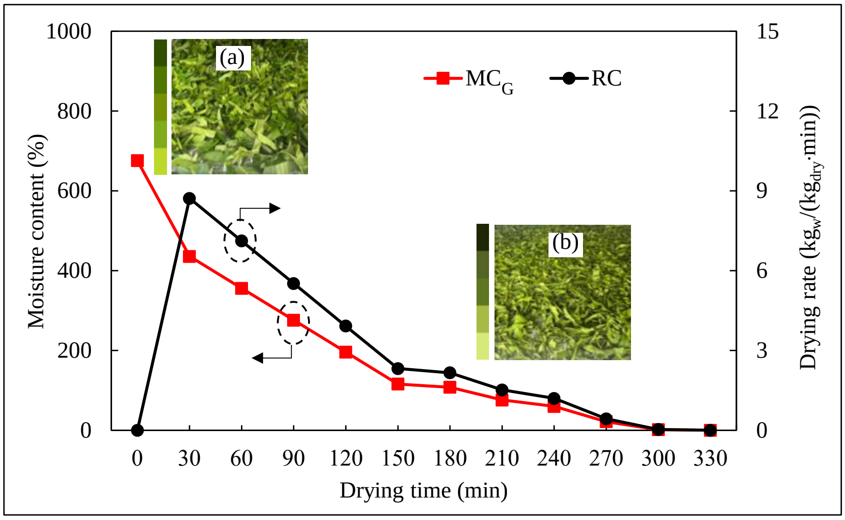

Figure 5 **Moisture content and drying rate the drying process**

Figure 6 shows the specific moisture extraction rate (SMER) and humidity ratio (ω, g_w/kg_{air}) inside the drying chamber. The average SMER value of the 240-minute drying period is 0.062 kg_W/kWh, which is nearly with that of Hossaina et al [21] of 0.038 kg_W/kWh. At the same time, the humidity ratio of drying air is approximately 29.72 g_W/kg_{da} during the drying period.

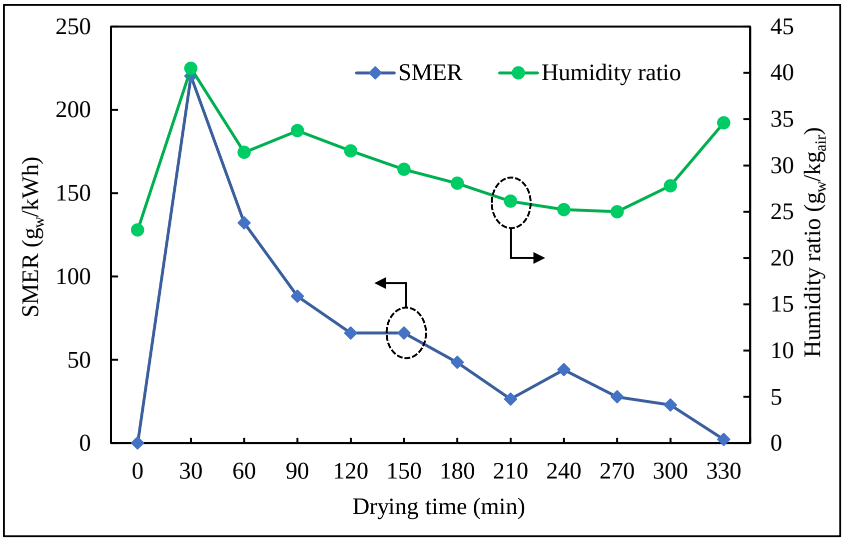

Figure 6 SMER and humidity ratio of the drying chamber

Figure 7 shows the drying efficiency, COP, and EER. Drying efficiency is approximately 51.18-74.92%, which corresponds with that of Singh et al [22] of 50.9% and Hossaina et al [21] of 78.23%. The COP impact slightly decreases, when the condenser temperature increases. This effect is directly driven from the temperature difference between heat source and heat sink. The minimum and maximum COPs of approximately 4.88 and 5.43 are found from the hot air temperature of 60 ^{o}C and 45 ^{o}C, respectively. The COP of this work is nearly with that of Aktas et al [23] of 5.25 and Hossaina et al [21] of 5.45. Energy efficiency ratio of drying chamber is approximately the range of 2.05-2.59 kW_{th}/kW_e. The EER result is correspondingly with the drying energy. The average thermal impacts of the drying chamber are presented in Table 3.

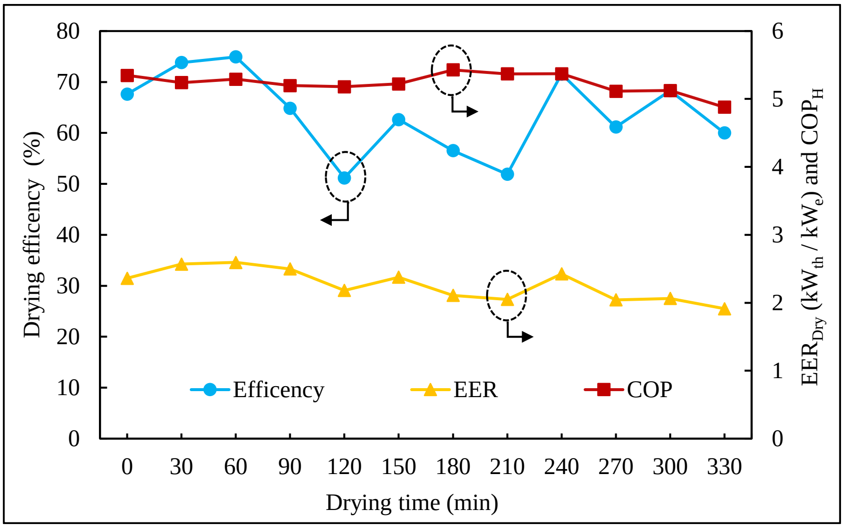

Figure 7 Efficiency and EER of the heat pump system

Table 3 Operating condition of Gymnema tea at the operation time of 240 minutes.

Properties	Value	Unit
Temperature in drying chamber (T_{ave})	45	°C
Temperature ambient (T_{amb})	32.9	°C
Relative humidity in drying chamber (RH_{ave})	41.00	%
Relative humidity ambient (RH_{amb})	62.7	%
Initial mass of Gymnema ($M_{G,s}$)	2	kg_G
Mass of Gymnema ($M_{G,t}$)	0.42	kg_G
Mass water of Gymnema ($M_{G,t}$)	0.09	kg_w
Mass of moisture content 0% ($M_{F,0}$)	0.23	kg_G
Moisture (WB)	22.50	%wb
Drying rate (DR)	0.27	$kg_w/(kg_G \cdot min)$
Moisture content (MC)	60	%
Latent heat of evaporation (h_{fg})	2420.06	kJ/kg_w
High absolute pressure (P_H)	2.29	MPa
Low absolute pressure (P_L)	0.37	MPa
Refrigerant temperature 1H (T_{1H})	28.6	°C
Refrigerant temperature 2H (T_{2H})	53.2	°C

Table 3 Operating condition of Gymnema tea at the operation time of 240 minutes. (continued)

Properties	Value	Unit
Refrigerant temperature 3H (T_{3H})	32.1	^{o}C
Enthalpy 1H (h_{1H})	422.4	kJ/kg
Enthalpy 2H (h_{2H})	461.8	kJ/kg
Enthalpy 3H (h_{3H})	250.5	kJ/kg
Heat capacity of drying chamber (Q_{Dry})	2.01	kW
Heat capacity of condenser (Q_C)	2.94	kW
Power consumption of drying chamber (W_{total})	0.824	kW
COP_H	5.37	-
η_{Dry}	71.56	%
EER_{Dry}	2.42	kW_{th}/kW_e
SEC	3.71	kWh/kg_G

Figure 8 shows the SEC and mass of Gymnema tea. The SEC is directly driven by electrical power consumption. The mass of Gymnema tea is inversely with the SEC and drying time. The appropriate drying time of 240 minutes specifies the SEC and material mass of 3.71 kWh/kg_G and 0.4 kg_G, respectively.

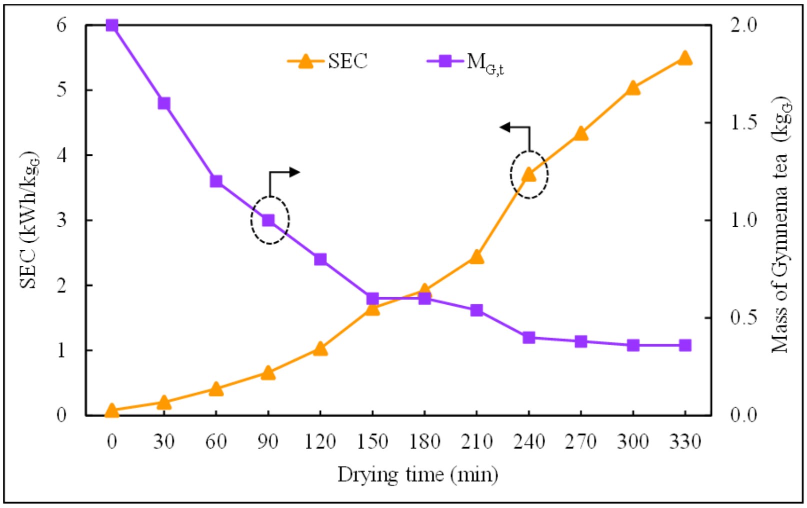

Figure 8 Specific energy consumption and mass of Gymnema tea

Figure 9 shows the correlation between the moisture content based on the dry-basis and drying rate parameters of the simulation and experiment. It was found that the dry-basis value from the simulation was lower than the experiment and was equal to 0 at 270 minutes, while from the experiment it was equal to 0 at 300 minutes because the predicted drying heat value was higher than the experiment and the heat loss due to the drying chamber wall was not taken into account.

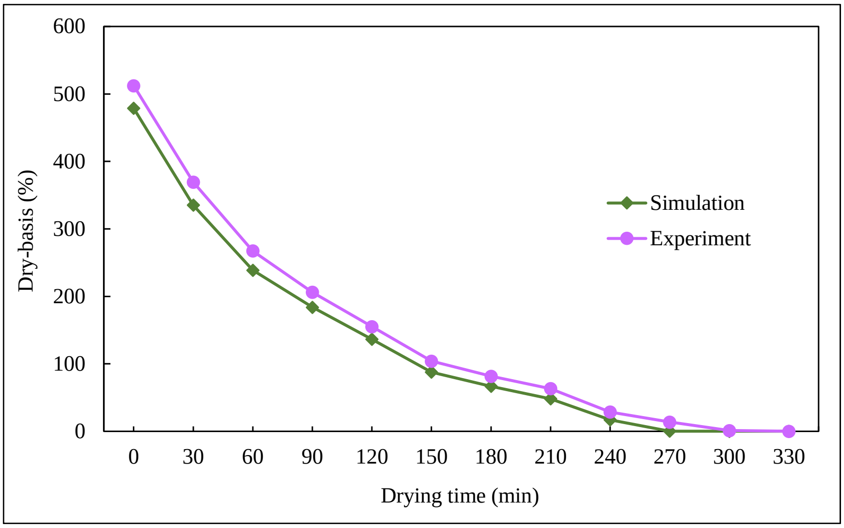

Figure 9 Simulation and experiment of moisture content based on the dry-basis and drying time of Gymnema tea

Currently, drying agricultural products is very important in terms of the economy and food security of Thailand. Therefore, it is an opportunity to expand this innovation to develop the community economy in a commercial way. The survey on reducing moisture of agricultural products uses a temperature range of 40-60 ^{o}C and requires cleanliness and precise temperature control. In the past, the heat pump dryer has been used for other agricultural products that need to be dried in this range, such as Assam tea, herbs, and coffee husks. The quality of the product after drying is very good.

4.3 Economic analysis

A total investment cost (TIC) of 2,789 USD and a maintenance cost of 279.80 USD/y (approximately 10% of investment cost) are the main expense costs of drying chamber. A discount rate of 7.05% [24], an operation time of 5 h/d and 200 d/y, and a lifespan of 10 y are assumed as the initial conditions to investigate the PB, NPV and IRR parameters. A market cost of dried Gymnema tea of 55.96 USD/kg_G is advantage from drying process, which is higher than a fresh Gymnema tea of 1.40 USD/kg_G or approximately an increase income rate of 40 times. Total income is approximately 5,372 USD/y, while reveals a power consumption of 119 USD/y. Payback period, net present value, and internal rate of return are 1.02 y, 16,366 USD, and 49.4%, respectively.

5. Conclusions

From above study results, it can be concluded as follows:

1) The novel R-134a vapor compression heat pump—R134a refrigerant, 0.746 kW compressor, 2.75 kW evaporator, 3.2 kW condenser, and 1 TR expansion valve—is implemented.

2) The CFD results—1.28 m/s wind speed, 101,324.56 Pa air pressure, and 58.77 ^{o}C hot air temperature—conduct the double drying blowers of 19 W/unit, ventilation fan of 10 W, 5 shelves, and intake air vent of 10 inch.

3) The optimal drying condition is the hot air temperature of 45 ^{o}C, drying time of 240 minutes, moisture content of 60% Wet-basis, drying rate of 1.20 $kg_w/(kg_G \cdot min)$.

4) Thermal performance of the drying chamber is performed as the drying efficiency of 71.56%, COP_H of 5.37, EER_{Dry} of 2.42 $kW_{th}/kW_{e,}$ and SEC of 3.71 kWh/kg_G.

5) Economic results in terms of the payback period, net present value, and internal rate of return are 1.02 y, 16,366 USD, and 49.4%, respectively.

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