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Research Article

Design of a Coal Drying System with Solar-Assisted Heat Pump and Waste Heat Utilisation

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Abstract

The increase in global energy demand has directed researchers towards making low-quality coals into an environmentally friendly energy source by reducing their high moisture content. Drying coal is a high-energy and time-consuming process, so reducing the required energy and drying time is crucial for drying technology. Coal drying increases the thermal value of coal and makes it easier to transport. In this study, a coal drying system was designed using waste heat recovery systems, R-134a refrigerant as working fluid, air source heat pumps, and vacuum tube solar collectors to provide hot air. Firstly, the moisture content of the coal and the desired moisture content after drying were determined, and then the heat required to dry the coal was calculated. Next, the capacity of the solar collector required to provide the necessary heat to the heat pump was determined, and the type and capacity of the heat pump that could produce the required heat were selected. Finally, the coal dryer was designed based on the specific requirements of the power plant and the type of coal used. As a result, the coal drying system designed with solar-assisted heat pumps and waste heat utilization can increase the efficiency of coal-fired power plants by reducing the moisture content of coal before combustion.

Keywords: *Coal; drying; heat pump; solar energy; waste heat recovery*.

1. Introduction

Drying is a high-energy and time-consuming process, so reducing the amount of energy required and the drying time is an important issue for drying technology. The energy required for drying in drying systems is crucial in evaporating moisture from the product. Heat transfer in a drying process can be achieved through conduction, convection, and radiation. In classical coal dryers, heat transfer occurs through conduction and convection [1], but in recent years, radiation heating methods such as microwave [2], infrared radiation [3], ultraviolet, and radio waves [4] have been given more attention, especially due to their low energy consumption.

In a study conducted by researchers in [5], using a pilot-scale fluidized bed dryer, they examined the effect of fluidization velocity on coal classification and drying. They found that coal dried quickly, and the moisture content of the product particles was below 2%, and the optimum classification efficiency was 92% by weight at a fluidization velocity of 2.2 m/s. In another study where low-grade coal with high moisture content was dried in a new disc dryer equipped with heating plates and rotary blades, the moisture content of the raw coal dropped from 34% to below 3% within 5 minutes at a heating plate temperature of 150°C [6]. In [7], the drying performance of a solar-biomass hybrid batch type horizontal fluidized bed dryer with a multi-stage heat exchanger and a heat pump for drying rice was investigated, and it was found that the heat recovery drying system provided a thermal energy saving of approximately 46.7% compared to the non-heat recovery drying system. In [8], a numerical model was proposed to estimate the energy performance of a solar energy dryer supported by a heat pump under terrestrial climates. It was confirmed that conventional solar dryers are not suitable for terrestrial climates with low ambient temperatures, and the heat pump dryer reduced the initial moisture content of the product from approximately 74% to around 19% in 21 hours.

In the study where a convective closed-loop solar-assisted heat pump dryer was designed for both simple heat pump drying and solar-assisted heat pump drying modes, it was concluded that the solar-assisted heat pump drying system performed better in every aspect [9]. In [10], dual-pass parallel flow, compartmentalized parallel flow, and non-compartmentalized parallel flow solar air collectors were designed for drying application, and celery roots were dried and examined as the product. It was observed that the highest instantaneous efficiency was achieved in the dual-pass parallel flow solar air collector (84.30%). In [11], researchers compared parallel flow (PPSAH), double-pass (DPSAH), and V-groove type (VTPSAH) solar-powered air heaters under the same climate conditions. They obtained exergy efficiency values in the range of 14.62–18.95% (VTPSAH), 12.28–15.68% (DPSAH), and 6.68–9.74% (PPSAH) using numerical and experimental approaches. In a study where vertical photovoltaic-thermal (PVT) solar dryers were analyzed using numerical and experimental approaches and fins were integrated on the absorber plate and PV panel to increase heat transfer, it was found that the thermal efficiency values of the vertical PVT collectors without fins and with fins were in the ranges of 47.46-

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54.86% and 50.25-58.16%, respectively, and that high air flow rate significantly improved drying performance in the finned vertical dryer [12]. In [13], V-groove three-pass (V-TPSAH) and V-groove four-pass (V-QPSAH) solar-powered air heaters were designed for drying municipal sewage sludge. Two different types of drying chambers (DC-I: conventional, DC-II: solar absorber) were integrated into each solar-powered air heater. According to experimental results, the average efficiency of the solar-powered air heater was found to be in the range of 70.12–81.70%.

Table 1 presents some products dried in heat pump, solar-assisted, and waste heat recovery drying systems. Energy consumption reductions of these new type dryers compared to traditional drying systems are shown.

Table 1. Some Dryer Types and Dried Products.

Product	Dryer Type	Reduction of energy consumption (%)	COP	Reference
Daphne	Heat pump, controlled by PLC	25	3.2	[14]
Melon	Infrared, solar energy, waste heat recovery assisted	33.4	-	[15]
Stale bread	Infrared, with heat pump	43.2	3.7	[16]
Mint leaf	Heat pump, waste heat recovery	48	3.94	[17]
Kiwi	Infrared, waste heat recovery	32.17	-	[18]
Carrot	Heat pump and Infrared, assisted heat pump with heat pump	50 & 22	2.96	[19]
Apple	Heat pump	-	3.02	[20]
Pumpkin seeds	Infrared, heat pump, PLC controlled	-	4.86	[21]
Grape pulp	Heat pump	51	3.28	[22]
Lemon	Infrared, with heat pump	11	2.74	[23]
Mint leaf & Apple	Solar air dryer and Infrared assisted solar air dryer	26.46 & 8.59	2.43	[24]
Mint leaf	PV/T with heat pump	12.27 (electrical); 53.66 (thermal)	4.18	[25]
Honey	Heat pump	27.11	2.65	[26]
Walnut	Heat pump, waste heat recovery and Infrared, waste heat recovery	6.54 & 7.94	3.34 & 3.14	[27]

Due to their porous structure and clay-based minerals, coals contain a significant amount of moisture. Lignites, which have high moisture content (40-60%), are also defined as low-quality coal because of their low heating value [28]. While most of the moisture, which is eliminated through processes such as filtration and centrifugation, is removed chemically bound with the coal, the residual moisture content can be removed by drying. A 1% reduction in moisture content results in an average increase of 40-60 kcal/kg in the heating value of coal [29]. Moisture not only adds unnecessary weight during transportation and storage of coal, but also increases operational costs. It decreases the friability of coal and makes blending operations more difficult [30]. Research has shown that lignites spontaneously ignite at low temperatures, around 40-50°C [31-33]. A study was conducted on Canadian lignite coal, which was dried using hydrothermal processing, vacuum drying, and hot air drying methods at different temperatures. Hydrothermal processing reduced the moisture content from 34% to 9.65% in 30 minutes at 325°C. On the other hand, moisture content reduction was similar in the 7-hour vacuum drying process at 70°C and the 110-minute hot air drying method [34]. In a pilot plant similar to a cyclone with a conical tube, a computational fluid dynamics study demonstrated a significant reduction in moisture content, up to 86.37% under optimal conditions, uniform liquid distribution, and significant volatile combustion [35]. When coal with high moisture content is burned in public utility boilers, a significant portion of the energy (7-10%) is consumed to evaporate the moisture, leading to decreased plant efficiency, increased fuel consumption, and higher flue gas emissions [36]. The moisture content of lignite coal from the Victorian era can reach up to 66% [37], while anthracite can contain as little as 0.6% [38]. Some Turkish and Czech Republic lignites contain 6%, and Australian lignite coal contains approximately 71% [39]. In conventional lignite power plants, up to 60% moisture content lignite coal is burned, and approximately 20% of the fuel energy is used in pre-combustion drying [40]. If moisture can be economically reduced, lignite coal's energy content can be increased and can compete with bituminous coal at an equal level [41]. Therefore, removing moisture from lignite coal is a crucial parameter.

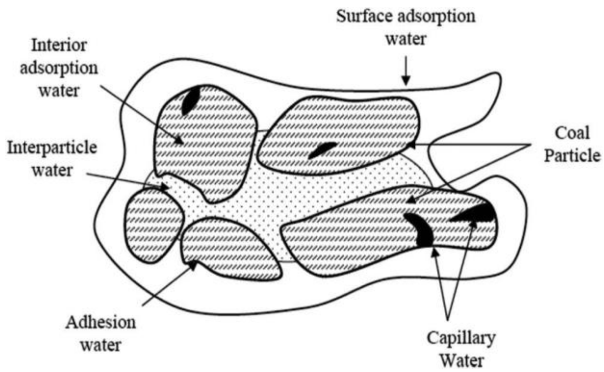

Figure 1. Different forms of water in the coal.

Different moisture conditions present in coal are shown in Figure 1 [36]. In each coal particle, internal adsorbed water is present between micro-pores and micro-capillaries, called natural moisture, which can be removed by thermal or chemical methods. Surface adsorbed water is present on the particle surface and is also considered natural moisture, which can be removed by thermal or chemical methods. Capillary water is natural moisture found in the capillary ducts of coal particles and can be removed by thermal or chemical methods.

In this study, a drying system will be designed for the Manisa province Soma Kısrakdere coal using waste heat recovery, the refrigerant fluid R-134a as the working fluid in a heat pump, and heat from vacuum-tube solar collectors with heat pipes. The drying chamber and the placement system for the wet product will be dimensioned and the drying system will be designed. The aim is to determine the power of the equipment in the drying system, the theoretical drying time of the coal, the specific humidity ratio extracted from the system, and the drying coefficient of the dryer.

2. Material & Method

The type of coal to be used in drying is the washed lignite coal, with hazelnut size, extracted from Kısrakdere location in Soma district of Manisa province, and its properties are given in Table 2 [42].

Table 2. Properties of Washed Hazelnut Charcoal in Soma Kısrakdere.

Variable	Industry	Corporate housing	Individual housing
Size (mm)	10 - 18	10 - 18	10 - 18
Humidity (%)	17.25	19	17
Ash (%)	11.47	16	17
Volatile matter (%)	35.34	35	40
Lower calorific value (kcal/kg)	4776	4750	4650
Upper calorific value (kcal/kg)	5077	5100	4830

On average, a hazelnut-sized coal is 0.015 m in diameter and weighs 0.017 kg [42]. Kısrakdere Coal has low ash (11.47%) and sulfur (0.96%) content, and has more efficient values than many fossil fuels in the industry, making it suitable for use in industrial facilities and the most appropriate and economical solution against the increasing heating and heating costs due to the widespread use of natural gas [43]. The specifications of the coal to be dried in the laboratory type drying system with a capacity of 75 kg and the coal table to be used in the drying chamber are given in Table 3.

Table 3. Specifications of The Coal to Be Dried and The Coal Table to Be Used.

Variable	Value	Unit
Coal size (diameter)	0.015	m
Wet weight of coal (grain)	0.017	kg
Wet weight of coal	75	kg
Coal quantity	4412	Piece
Coal bottom area	0.0007	m^2
Coal table top	0.7	m
Coal basin size	0.5	m
Coal field area	0.35	m^2
Coal basin	9	Piece

The materials and specifications used in the design of the drying chamber are shown in Table 4 [44, 45].

Table 4. Materials and Properties of the Drying Chamber.

Type of material	Thickness (m)	Thermal conductivity (W/mK)	Specific heat (kJ/kg°C)	Density (kg/m^3)
Exterior plaster lime cement	0.03	0.87	1.044	2100
Aerated concrete	0.2	0.11	1.17	350
Polyurethane insulation	0.03	0.030	1.05	42
Interior plaster lime plaster	0.02	0.7	0.828	2200

The system includes a solar collector, a heat pump, an air handling unit a waste heat recovery system, and a coal dryer.

Solar collector is used to collect solar radiation and convert it into heat energy. The collected heat is then transferred to the heat pump through a heat exchanger. Heat pump is used to increase the temperature of the air used for drying the coal. It can also extract heat from the waste heat sources and reuse it for the drying process. Air handling unit is used to distribute the heated air to the coal drying system. Coal dryer is used to remove the moisture from the coal. The heated air is blown into the coal dryer to dry the coal. Waste heat recovery system such as the exhaust gas from the combustion of coal or the waste heat from the heat pump, can be recovered and reused for the drying process.

The steps shown in Table 5 [19, 46-50] were applied for data analysis in the solar energy-supported heat pump dryer design.

Table 5. Equations Used in Data Analysis.

Step of data analysis	Equality		Equality number
Design of the drying chamber	The amount of heat energy required to heat the kiln walls to the system temperature of the drying air and to maintain that temperature (q_1)	$m_1 \times c_1 \times \Delta T$	(1)
	Amount of energy required to heat the drying air is this amount of energy (q_2)	$\rho \times V \times c_2 \times \Delta T$	(2)
	The energy required to heat the products to be dried (q_3)	$m_w \times c_3 \times \Delta T$	(3)
	The energy required to evaporate the moisture contained in the dried product (q_4)	$m_{wt} \times \theta_o$	(4)
	The energy required to cover the heat losses from the oven to the ambient air (q_5)	$K \times A_c \times \Delta T$	(5)
	Total heat transfer coefficient (K)	$\frac{1}{\frac{1}{h_i}+\frac{d_n}{k_n}+\frac{1}{h_d}}$	(6)
Calculation of the final moisture content of the coal	Moisture content by dry weight (MC_{dw})	$\frac{M_w - M_d}{M_d}$	(7)
	Moisture content by wet weight (MC_{ww})	$\frac{M_w - M_d}{M_w}$	(8)
Calculation of the payload from solar energy ($\dot{\boldsymbol{Q}}_{\boldsymbol{S}}$)		$\dot{V} \times \rho \times c \times \Delta T$	(9)
Electrical energy consumed by the fan ($\dot{\boldsymbol{W}}_{\boldsymbol{f,S}}$)		$\frac{\dot{Q}_S - \eta \times I \times A_a}{\eta}$	(10)
Heat pump calculation	Heat exchanger equation	$\dot{Q}_C = 1.25 \times \dot{Q}_{tot}$	(11)
	Condenser load ($\dot{Q}_C$)	$\dot{m}_{R-134a} \times (h_4 - h_1)$	(12)
	Evaporator load ($\dot{Q}_E$)	$\dot{m}_{R-134a} \times (h_2 - h_3)$	(13)
	Compressor load ($\dot{W}_{Comp}$)	$\dot{m}_{R-134a} \times (h_4 - h_3)$	(14)
	Heating coefficient of influence (COP_{sys})	$\frac{\dot{Q}_C}{\dot{W}_{Comp} + \dot{W}_{fan}}$	(15)
Specific moisture absorption rate ($\boldsymbol{SMER}$)		$\frac{\dot{m}_{wt}}{\dot{W}_{Comp} + \dot{W}_{fan}}$	(16)

3. Findings

The design of the system includes the following steps:

- Determination of the heating requirements of the coal dryer; the amount of heat required for drying the coal depends on the coal's moisture content, initial and final temperatures, and mass flow rate.
- Sizing of the solar collector; it depends on the heating requirements of the coal dryer and local solar radiation conditions.
- Sizing of the heat pump; it depends on the heating requirements of the coal dryer and the temperature increase required by the heat pump.
- Design of the waste heat recovery system; it is designed to recover as much waste heat as possible from the heat pump and other sources.
- Design of the control system; it is designed to optimize the operation of the system and ensure that the coal drying process is efficient and effective.

The ideal moisture content in coal stocks should be between 8-10% [51]. By using Eqs. (7) and (8), it was found that 5.77 kg of water evaporates from the coal. If the drying air temperature is at 35 °C [52], it was calculated that the moisture content will decrease from 17% to 8% in 95 minutes [53].

The system diagram is shown in Figure 2. The mechanical system that consumes three energies, including a fan, compressor, and pump, and three heat exchangers (condenser and evaporator), including a plate heat exchanger used in waste heat recovery, an expansion valve, temperature and relative humidity sensors, a vacuum tube solar collector, a drying chamber, a product tray, and a weight scale are included in the system. An electronic control panel is installed for controlling the drying air. The temperature of the drying chamber is controlled by adjusting the heat pump unit to achieve uniform drying conditions (Table 6).

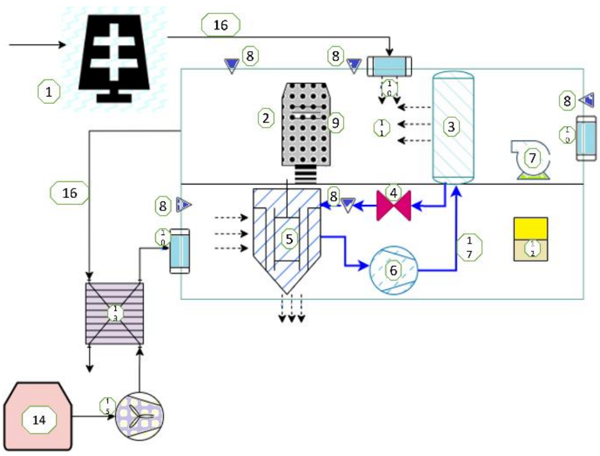

Figure 2. System overview.

Table 6. System Equipment.

Number	Name	Number	Name
1	Solar collector	10	Fresh air
2	Drying chamber	11	Mixed air
3	Condenser	12	Electrical Control Unit
4	Throttling valve	13	Plate heat changer
5	Evaporator	14	Waste heat plant
6	Compressor	15	Power plant fan
7	Fan	16	Air line
8	Thermo-Hygrometer	17	Refrigerant line
9	Coal graine		

The height of each tray in the drying chamber is 0.05 m. In the design, 0.05 m gaps were left at both ends of the trays, and a drying chamber of 0.8 m × 0.6 m × 0.7 m was created.

As seen on the psychrometric chart given in Figure 3, air entered the drying system at point T_i with 46% relative humidity and a temperature of 35°C [54]. After going through the cooling and dehumidification processes with 80% moisture removal efficiency, the air left the drying chamber at point T_o with a temperature of 27°C. The mass of the circulating air (m_2) was found to be 2165.6 kg.

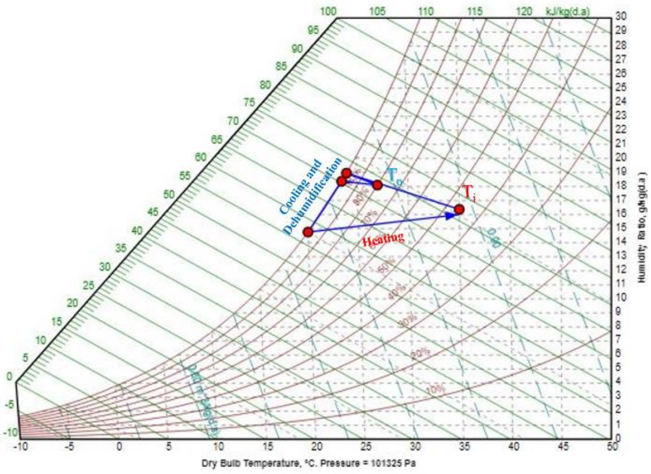

Figure 3. Psychrometric chart.

To heat the air in the drying system, a vacuum tube solar collector with 57.16% efficiency was used [55]. The power of the vacuum tube solar collector should be enough to compensate for the heat loss in the drying system. The values of the heat calculation for the drying chamber are shown in Table 7.

Table 7. Calculation of The Drying Room Temperature.

Variable	Value	Unit	Variable	Value	Unit
t	95	min	A_a	60.24	m²
$\mathbf{c_2}$ [56]	1.0057	kJ/kg°C	A_d	0.48	m²
$\mathbf{c_3}$ [57]	1.883	kJ/kg°C	h_i	7	W/m²K
$\mathbf{m_{wt}}$	5.77	kg	h_o	13	W/m²K
$\mathbf{m_2}$	2165.6	kg	K	0.322	W/m²K
$\mathbf{Q_0}$	2257	kJ/kg	q_1	76496.749	kJ
I [58]	560	W/m²	q_2	17423.551	kJ
$\mathbf{T_i}$	35	°C	q_3	2570.295	kJ
$\mathbf{T_a}$ [59]	16.8	°C	q_4	13022.890	kJ
$\mathbf{T_o}$	27	°C	q_5	96.204	kJ
ρ	1.2	kg/m³	$\dot{Q}_{tot}$	19.230	kW

An 80% effective heat exchanger was used for energy recovery from waste heat (50°C [59]), and the system air was heated from 27°C to 35°C.

The condenser capacity was taken as 25% more than the total energy required for the drying system to compensate for compressor resting [48]. R-134a was used as the refrigerant in the heat pump system. The heat pump calculation is shown in Table 8.

Table 8. Calculation of The Heat Pump.

Variable	Value	Unit	Variable	Value	Unit
$\mathbf{T_1}$	10	ºC	$\dot{m}_{R-134a}$	0.198	kg/s
$\mathbf{T_2}$	55	ºC	$\dot{m}_a$	1203.111	kg/h
$\mathbf{T_3}$	45	ºC	c_a	1.005	kJ/kgºC
$\mathbf{T_4}$	5	ºC	P_{atm}	101.325	kPa
$\mathbf{P_1}$	349.9	kPa	η_{ws}, $\eta_{w,c}$	0.80	
$\mathbf{P_2}$	1163	kPa	$\eta_{w,e}$	0.95	
$\mathbf{h_1}$	253.34	kJ/kg	η_w	0.76	
$\mathbf{h_2}$	284.17	kJ/kg	$\dot{Q}_C$	24.037	kW
$\mathbf{h_{2s}}$	278	kJ/kg	$\dot{Q}_E$	27.199	kW
$\mathbf{h_f, h_3, h_4}$	115.8	kJ/kg	$\dot{W}_{comp}$	6.096	kW
$\mathbf{h_g}$	237.35	kJ/kg	$\dot{W}_{fan}$ [60]	0.25	kW
$\mathbf{s_1, s_{2s}}$	0.9288	kJ/kgK	COP	3.788	

When the product is dried by convection, heat transfer occurs from the surface to the inside, while evaporation occurs from the cells inside to the surface. The specific moisture extraction rate from the dryer (Eq. 16) was calculated as 910 g water/kWh.

4. Conclusions

In this study, a laboratory-scale drying system was designed for the drying of Soma Kısrakdere coal in Manisa province under summer conditions using waste heat recovery, solar energy, and a heat pump. The design of a coal drying system with solar-assisted heat pump and waste heat utilization involves integrating various technologies to improve the efficiency of coal-fired power plants. The design should consider the specific requirements of the power plant and the coal being used to ensure optimal performance.

Overall, a coal drying system with waste heat recovery, solar energy support, and heat pump can be an important solution to increase the efficiency of coal-fired power plants and save energy. This system can help make low-quality coals into a more environmentally friendly energy source. Designed using solar energy, waste heat recovery, and heat pump, this system can reduce the energy required to provide hot air, which can shorten the drying time and reduce energy consumption. In addition, greenhouse gas emissions can be reduced thanks to this system. Therefore, a coal drying system with waste heat recovery, solar energy support, and heat pump can be an important step towards a more efficient, environmentally friendly, and sustainable coal-fired power plant.

Nomenclature

A_a	Air duct arms area (m^2)
A_d	Dryer area (m^2)
c_1	Total specific heat of wall materials (kJ/kgºC)
c_2	Specific heat of drying air (kJ/kgºC)
c_3	Specific heat of coal (kJ/kgºC)
h_1	Condenser outlet enthalpy value (kJ/kg)
h_2	Throttling valve outlet enthalpy value (kJ/kg)
h_{2s}	Throttling valve outlet isentropic enthalpy value (kJ/kg)
h_3	Evaporator outlet enthalpy value (kJ/kg)
h_4	Compressor outlet enthalpy value (kJ/kg)
I	Value of solar radiation (W/m^2)
M_i	Wet weight (kg)
M_d	Dry weight (kg)
m_1	Mass of the wall (kg)
m_2	Mass of air to circulate in the plant (kg)
m_{wt}	Water to be extracted (kg)
P_{atm}	Atmospheric pressure (kPa)
P_s	Saturation pressure of water vapor (kPa)
$\dot{Q}_C$	Condenser load (kW)
$\dot{Q}_E$	Evaporator load (kW)
s_1	Condenser outlet entropy value (kJ/kgK)
$SMER$	Specific moisture extraction rate (g water/kWh)
T_a	Air temperature (ºC)
T_1	Condenser outlet temperature (ºC)
T_2	Throttling valve outlet temperature (ºC)
T_3	Evaporator outlet temperature (ºC)
T_4	Compressor outlet temperature (ºC)
V	Drying air volume (m^3)
$\dot{V}$	Total air flow (m^3/s)
$\dot{W}_{comp}$	Compressor load (kW)
θ_o	Latent heat of evaporation at evaporation temperature (kJ/kg)
ρ	Density of air (kg/m^3)
$\eta_{w,c}$	Condenser efficiency
$\eta_{w,e}$	Evaporator efficiency
φ	Relative humidity

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