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Heat pump drying of industrial wastewater sludge

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Abstract

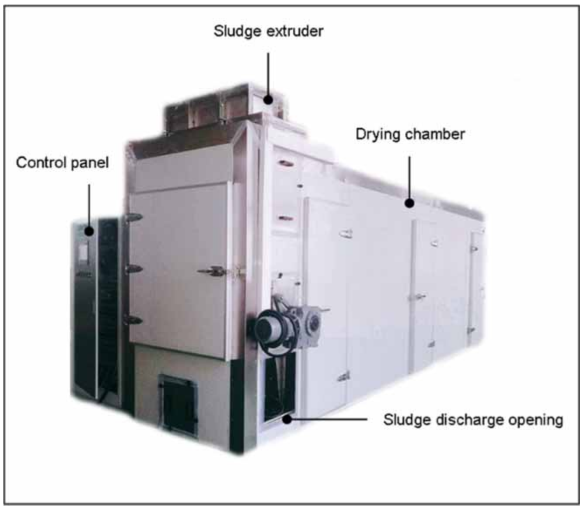
The popularity of heat drying of wastewater sludge has increased over the past several years because it can reduce sludge mass and volume, and hence disposal costs. However, drying sludge using conventional combustion-heated dryers is energy-intensive. Heat pump dryers can be efficient and offer significant energy savings by recycling the drying heat. This paper describes a heat pump dryer designed for continuous drying of industrial wastewater sludge. The dryer constructed was essentially a closed-loop air system. The air used for drying is dehumidified to recover the latent heat of vaporization, re-heated using the recovered heat, and recirculated in a closed environment. The closed-loop layout eliminates emissions of dust, malodorous gases, and volatile compounds, obviating the need for exhaust treatment otherwise required to meet environmental regulations. Data on the moisture extraction rate, specific moisture extraction rate, and specific energy consumption are presented and discussed.

Key words: belt dryer, drying, energy efficiency, heat pump, sludge

Highlights

- Wastewater sludge was dried in a continuous, enclosed heat pump dryer.
- No emissions of dust, malodorous gases, and volatile compounds.
- Sludge moisture content was reduced from 82% to $<$13% after 120 minutes of drying.
- The dryer was highly energy efficient, using 0.28–0.36 kWh of electricity to remove one kg of water.

Graphical Abstract



INTRODUCTION

Typically, the biological treatment of industrial wastewater generates large amounts of sludge. In China, the major outlets for industrial wastewater sludge are off-site incineration and landfill. The costs of these options are increasing rapidly and, for hazardous sludge, can be up to 900 USD per tonne. Such high costs have led to searches for viable and cost-effective sludge disposal solutions. Reducing the sludge volume mechanically is no longer sufficient as the dewatered sludge still contains 70–80% water. Thermal drying has attracted much attention owing to high dehydration rates and the ability to reduce water content to 10% or less (Arlabosse *et al.* 2012; Bennamoun *et al.* 2013).

Thermal drying methods were first developed for the chemical and food processing industries (Nonhebel & Moss 1971; Keey 1978; van't Land 2012). The wide range of technologies available reflects the diversity of the chemicals and foodstuffs being dried. Some evaporative dryer technologies have been adopted, with modifications, for drying sludge (Tunçal & Uslu 2014; Chen *et al.* 2015). Sludge drying involves heating to evaporate water and evaporation requires large amounts of energy. Common sludge dryer types can be classified by the manner in which heat is transferred to the wet solids: direct or indirect. Direct dryers accomplish convective drying by contact between the wet sludge and a hot gas, usually heated air, which also removes the evaporated moisture. Examples of direct drying systems used for sludge include fluidized bed, rotary, belt (or band/conveyor), and flash dryers. Indirect (or contact) drying involves bringing the wet sludge into contact with a surface heated by steam or hot oil, with a sweep gas to remove the water vapor released during drying. Disc, paddle, and thin film dryers employ this method. Some dryers use a combination of the two modes.

Several matters need consideration when selecting drying technology, including potential operating issues. For instance, sticky sludge buildup is of particular concern in some of the technologies noted. When sludge is partly dry it becomes sticky, which makes it cling to the dryer walls, impairing performance and reliability (Li *et al.* 2013, 2014). One industrial sludge dryer suffered significant unscheduled downtime because of the need to remove sticky sludge (Peeters 2010). Although several control strategies have been proposed to tackle sludge stickiness in drying sludge (Li *et al.* 2012; Peeters *et al.* 2013, 2014), their practical implementation will add operating complexity and costs to the process.

Sludge dryers operating in open-loop layouts – i.e. the drying medium is exhausted to the atmosphere – must deal with air pollution issues. Because the sludge is agitated and entrained in the hot air flow in direct dryers – e.g. flash, rotary, and fluidized bed dryers – substantial dust generation is unavoidable and becomes an air pollution problem (Jumah & Mujumdar 2015), and good dust control is essential. In addition to being a health concern, dust formation during drying is an explosive hazard. In the past, sludge drying installations have experienced fires and explosions. Some sludge dryers operate at high temperatures (>100 °C) which promotes the emission of malodorous gases and volatile compounds (Deng *et al.* 2009; Ding *et al.* 2015; Liu *et al.* 2015; Weng *et al.* 2015; Zheng *et al.* 2017; Wu *et al.* 2018), presenting yet another emissions abatement burden. Modern sludge drying plants must be fitted with appropriate exhaust gas cleaning equipment, which can represent significant additional capital cost.

Heat drying is the most effective way of minimizing the mass and volume of sludge, but evaporative drying is energy-intensive. Clearly the dryer's operator and/or process designer must select a process that is both energy-efficient and able to avoid the operating issues discussed. This paper describes the use of a belt dryer based on heat pump technology to dry industrial wastewater sludge from a chemical plant, highlighting its energy-efficiency, operating simplicity, and environmental performance.

HEAT PUMP DRYING TECHNOLOGY

Heat pumps extract heat from a low temperature source and give it off at a higher temperature where it can be used beneficially (Alves-Filho 2016) – see Figure 1. Such pumps operate by taking a quantity of

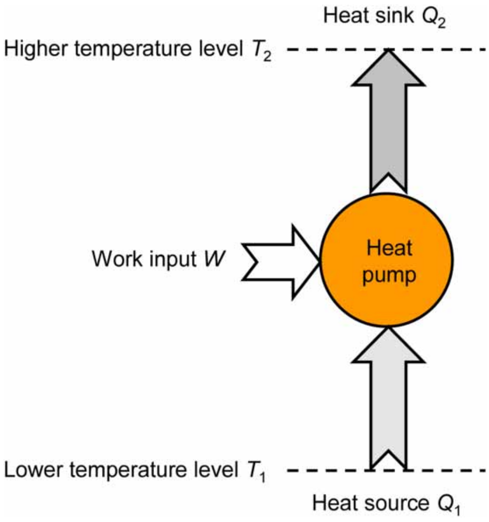


Figure 1 | Simple heat pump.

heat, Q_1, at temperature T_1, adding some work, W, and delivering more heat, Q_2, to a heat sink at higher temperature, T_2 – i.e., the heat Q_1 at temperature T_1 is 'pumped' to the higher temperature level, T_2. Heat pumps are the only heat recovery system capable of raising the temperature of low-grade heat.

There are many different types of heat pump but the commonest is the mechanical vapor compression heat pump, which uses a motor-driven compressor – see Figure 2. There are two, linked, cyclic processes: the heat pump and air drying cycles.

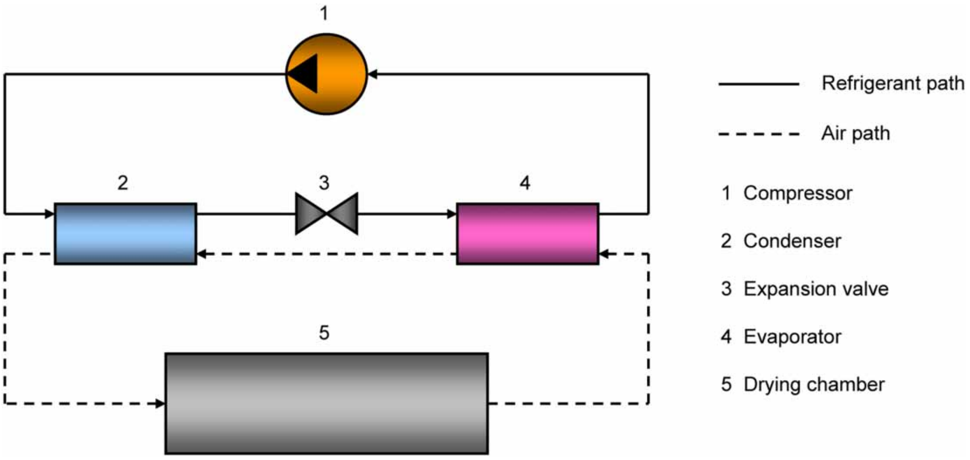


Figure 2 | Schematic of the refrigerant and air cycles of a basic heat pump dryer.

The heat pump shown schematically in Figure 2 includes only the major components, the compressor, condenser, expansion valve, and evaporator. The solid line represents the refrigerant path. In the evaporator (item 4), the refrigerant evaporates by extracting heat from the heat source. The compressor (1) increases the pressure and temperature of this vapor, which condenses in the condenser (2), giving up its latent heat to the heat sink. The condensed liquid refrigerant expands through the expansion valve (3) and enters the evaporator, restarting the cycle. The heat pump simultaneously cools and heats in different locations, the evaporator and condenser sides of the cycle, the former absorbing and the latter rejecting heat.

The air circulation loop – the broken line in Figure 2 – interacts with the refrigerant circuit at both the evaporator and condenser. Warm, moist air is withdrawn from the drying chamber (5) and passed over the evaporator, where it is cooled below its dew point, so that water vapor condenses. The condensed water is discharged and the cooled, dried air enters the condenser where it is reheated by the latent heat of condensation combined with some of the heat absorbed in the evaporator. With its drying potential restored, this hot, relatively dry air is then passed back into the drying chamber. Heat pump drying can thus provide a latent heat recycling mechanism.

RESULTS AND DISCUSSION

Vapor compression heat pump

The heat pump dryer used in this study comprised two distinct parts, a vapor compression heat pump and a drying chamber. Heat pump design involves specifying all components – that is, the compressor, evaporator, condenser, expansion valve, liquid line filter, check valve, shut-off ball valve, high/low pressure switch, etc. Sometimes, additional components are included to enhance performance. The system used in the study had two additional components, incorporated in the refrigerant and air cycles – both added to improve system efficiency.

The two additions were a 3-in-1 apparatus and a recuperator/economizer – items 3 and 6 in Figure 3 respectively – in the standard refrigerant and air cycles. The 3-in-1 apparatus is a combined suction line accumulator, liquid receiver, and heat exchanger. The latter part uses the cold refrigerant leaving the evaporator (5) to cool the warm liquid refrigerant from the condenser (2). This ensures superheating of the refrigerant vapor before it goes to the compressor (1) and sub-cooling of the liquid refrigerant before it enters the evaporator coil via the expansion device (4). The recuperator is an

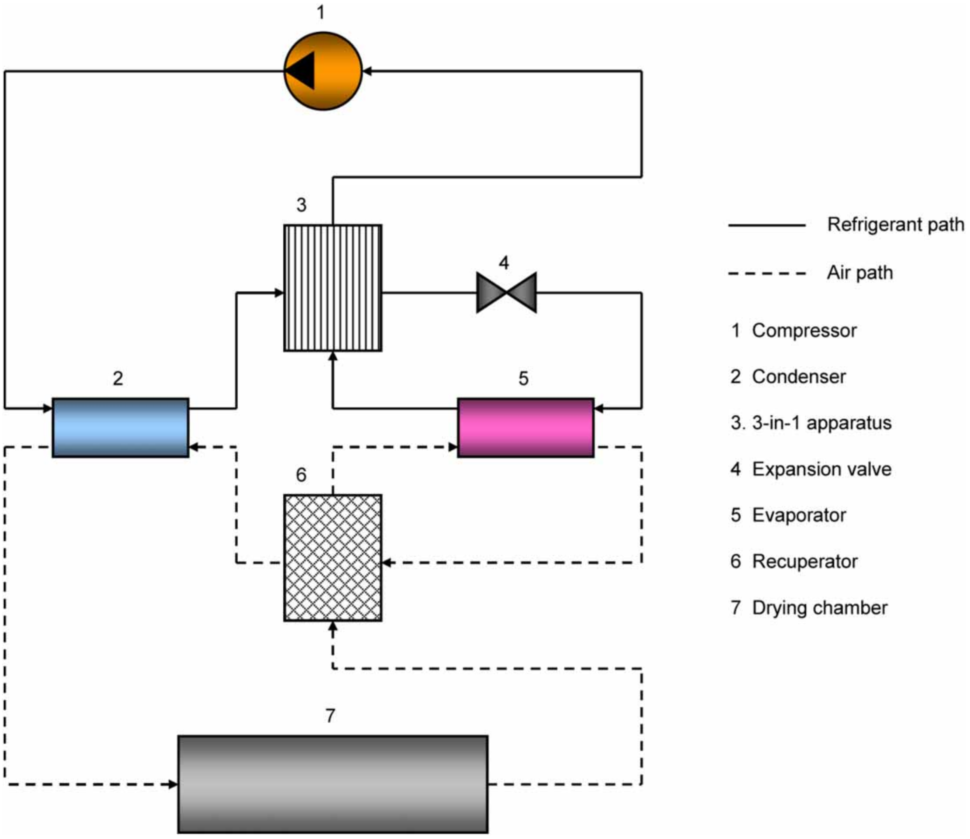
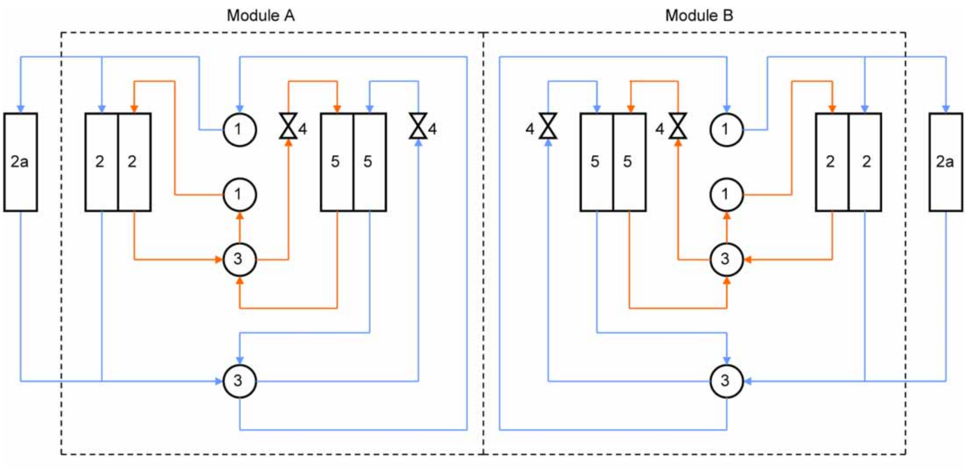


Figure 3 | Schematic of heat pump dryer's refrigerant and air cycles with additional components.

air-to-air plate heat exchanger within the air path (Pereira *et al.* 2004). It exchanges heat between the evaporator's warm inlet and cold outlet air without transferring moisture. In other words, it carries some of the cooling load that would otherwise be carried by the evaporator, by pre-cooling the air entering the evaporator and at the same time pre-heating the air entering the condenser. The pre-cooling reduces the air temperature closer to its dew point and raises the air humidity going into the evaporator, thus enhancing the evaporator's dehumidification capability (Chua & Chou 2005).

The heat pump system comprises four identical modules, each consisting of two independent refrigerant circuits, giving a total of eight such circuits. Figure 4 shows two modules bolted together. A fan delivers moisture-laden air from the drying chamber to each module, where the moist air is cooled and dehumidified using the two evaporators in series (item 5). After water vapor removal, the now cold and dry air stream is heated to the desired temperature in the two condensers, also in series (2). One of the two refrigerant circuits in each module is equipped with an external air-cooled condenser (2a). Some heat is exhausted by the external condenser to balance the heat of compression added to the module. Major component details for the system are given in Table 1.



1 Compressor; 2 Condenser; 2a External condenser; 3 3-in-1 apparatus; 4 Expansion valve; 5 Evaporator

Figure 4 | Schematic diagram of identical module pair, each comprising two refrigerant circuits.

Drying chamber

A belt-type drying chamber was used in this study. Two permeable belts were installed, one above the other with the upper one discharging onto the lower. The drying chamber operated by blowing hot air vertically through sludge carried on the belts, which moved horizontally through the drying chamber. The hot air flowed upwards, moved through the belts by fans – see the plan view in Figure 5. The conveyor belts and heat pump system are inside an enclosed, insulated structure, which has a sludge extruder on the top (Figure 6). Residence time in the belt dryer could be varied by operating at different belt speeds. The conveyors were driven by 3 kW motors. The amount of sludge processed at any given belt speed can be varied by changing the sludge extrusion rate and hence the depth of sludge dropped onto the top belt. The sludge belts are stationary during drying and, as the air velocity used is relatively low, very low levels of dust generation and fines entrainment arise, enabling drying air recirculation within the closed-loop layout. The drying chamber's dimensions are 6.5 (L) × 1.2 (W) × 2.4 m (H).

Table 1 | Specifications of major heat pump components

Component	Quantity	Specifications
Compressor	8	Scroll compressor Nominal rating: 4.5 kW Swept volume: 17.2 m^3/h
Fan	4	Centrifugal fan Power input: 3 kW Speed: 2,870 rpm
Evaporator	8	Aluminum fin & copper tube heat exchanger Face area: 0.32 m^2 Tube OD: 9.52 mm Number of tube rows: 4 Number of circuits: 9 Tubes per circuit: 8 Fin spacing: 2 mm
Condenser	8	Aluminum fin & copper tube heat exchanger Face area: 0.36 m^2 Tube OD: 9.52 mm Number of tube rows: 3 Number of circuits: 18 Tubes per circuit: 6 Fin spacing: 2 mm
External condenser	4	Aluminum fin & copper tube heat exchanger Face area: 0.8 m^2 Tube OD: 9.52 mm Number of tube rows: 4 Number of circuits: 16 Tubes per circuit: 8 Fin spacing: 2 mm
Expansion valve	8	Thermostatic Rated capacity: 37 kW
3-in-1 apparatus	8	Suction line accumulator volume: 2.4 L Liquid receiver volume: 3.1 L
Refrigerant	n/a	R134a Boiling point: –26.1 °C Global warming potential: 1,430

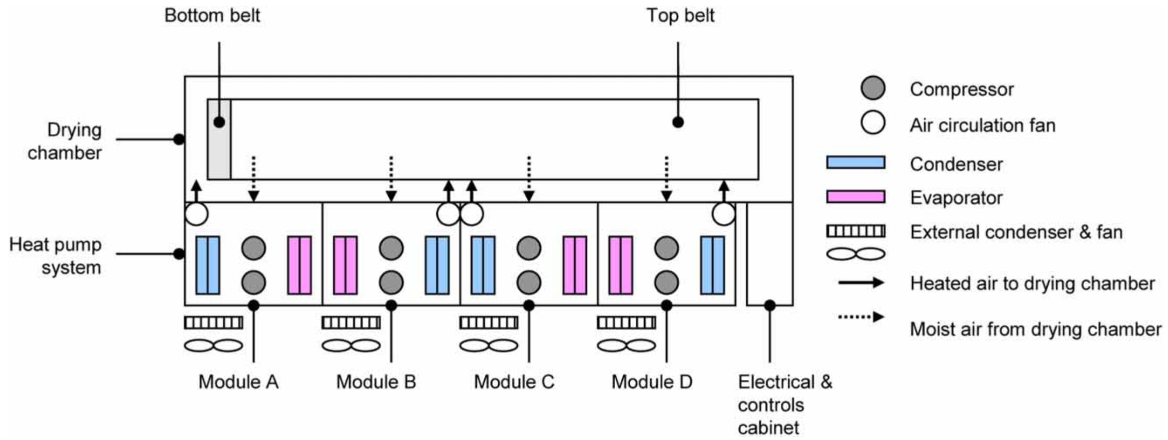


Figure 5 | Plan view of the heat pump dryer.

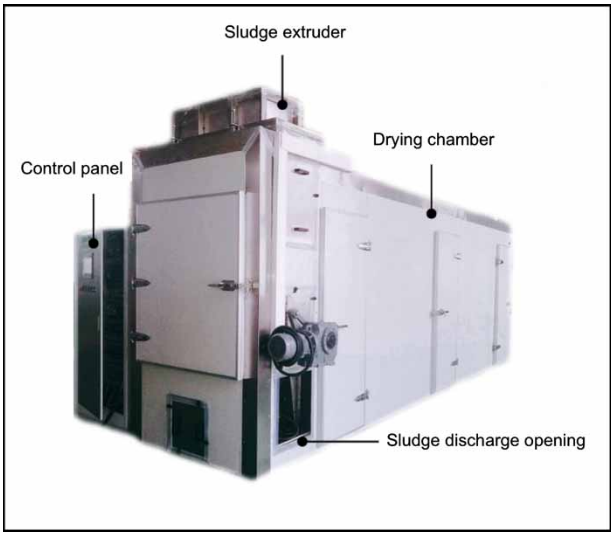


Figure 6 | Heat pump dryer constructed for the study.

Heat pump dryer performance

The heat pump dryer's operation was regulated using a PLC to provide full control. When drying started, the fans were activated and the recirculating air stream was pre-heated to 30 °C using an electrical resistance heater. Once that temperature was reached, the heat pump system was turned on. The resistive heater stayed on until the air entering the drying chamber reached 65 °C, when the sludge extruder and conveyor belt system were turned on to work together with the heat pump system.

Sludge drying tests were conducted at the wastewater treatment plant of a chemical manufacturing company in Jiangsu province, China. Several drying runs, each lasting 10–12 hours, were done using dewatered sludge from a screw press. In one such run, as an example, the dewatered sludge's initial moisture content varied within the range of 78–82% (wet basis). Dewatered sludge was transported from a bin into the sludge extruder via a screw conveyor.

It is well known that the rate of moisture removal in convective drying increases with the total surface area of sludge in contact with the drying medium. In this study, dewatered sludge was extruded to create long, thin strings, providing a large surface area (Figure 7). Heat was transferred to the sludge strings on the upper and lower belts, which moved intermittently, by circulating air between the heat

Figure 7 | Dewatered sludge being extruded.

pump system and the drying chamber. The sludge extruder was also operated intermittently, in synchrony with the belt operation. The typical air velocity through the belts was 1.5 m/s.

The dried product was removed by a screw conveyor. Sludge residence time was 120 minutes. Under these conditions, the sludge's final moisture content was in the range of 8–13%. (Figure 8 shows sludge samples before and after drying.) For this run, the heat pump dryer operated for 12 hours, during which time the temperature of air entering the drying chamber remained close to 65 °C, under control of heat rejection by the external condenser of each module.

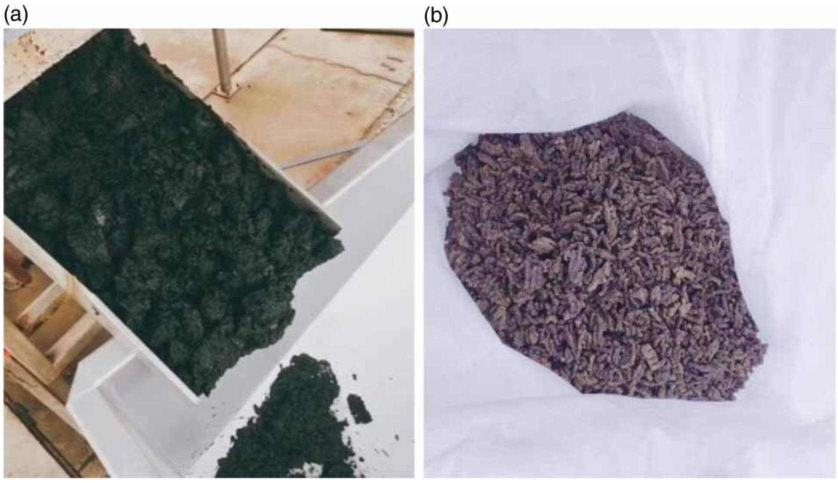


Figure 8 | Dewatered sludge (a) before and (b) after drying.

The effectiveness of a vapor compression heat pump is usually expressed in terms of the coefficient of performance (COP) – Equation (1):

$$\mathrm{COP} = \frac{\text{Useful heat ouput}}{\text{Power input}} \tag{1}$$

The COP implies that the heat pump's purpose is to produce heat at a high enough temperature for beneficial use. However, since both heating and cooling (dehumidification) effects are sought in heat pump drying, performance is characterized better as the amount of water extracted per unit of energy input. This is the specific moisture extraction rate (SMER) – Equation (2):

$$\mathrm{SMER} = \frac{\text{Amount of water evaporated}}{\text{Energy input to dryer}}, \quad \mathrm{kg/kWh} \tag{2}$$

where kWh is the electrical energy consumption, which, for combustion-heated dryers, refers typically to primary fuel energy consumption plus electrical power for dryer operation.

Another option is the specific energy consumption (SEC) given by Equation (3). This is the reciprocal of SMER and can be used to compare energy efficiencies between different dryer types.

$$\mathrm{SEC} = \frac{\text{Energy input to dryer}}{\text{Amount of water evaporated}}, \quad \mathrm{kWh/kg} \tag{3}$$

The moisture extraction rate (MER) – Equation (4) – normally expressed in kg-water per hour, is used to indicate drying capacity.

$$\mathrm{MER} = \frac{\text{Amount of water evaporated}}{\text{Drying time}}, \quad \mathrm{kg/h} \tag{4}$$

SMER, SEC, and MER are used as assessment criteria for the heat pump dryer's performance in this study. Figure 9 shows the MER as a function of operating time; each data point representing the mass of water extracted from the sludge in one hour. After the first two hours, the MER was relatively constant. The dryer is designed for continuous operation, so its throughput is best defined by the steady-state MER, which can be estimated from the curve in Figure 9 by ignoring the first two data points. The average steady-state MER for this run was 178 kg/h, corresponding to an evaporative capacity of about 4,300 kg per day. As noted, the sludge moisture content fell from 78–82% to 8–13% during drying. Because the heat pump system comprises modules that are bolted together, systematic throughput increases can be achieved easily by adding modules and increasing the belt length.

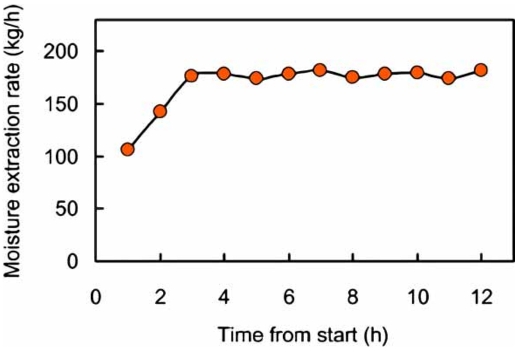


Figure 9 | Moisture extraction rate (MER) for the example drying run.

Figure 10 shows SMER as a function of operating time; each data point representing the mass of water extracted from the sludge in the preceding hour divided by total electrical energy use in that interval. The average steady-state SMER was calculated as 3.5 kg/kWh, corresponding to an SEC of 0.3 kWh/kg. A total of seven drying runs were conducted, giving SEC values in the range of 0.28–0.36 kWh/kg. There is little research on sludge drying using heat pumps. Zhang & Zhu (2018) describe a small, batch-mode, heat pump system for drying sludge, having a maximum inlet air temperature of 55 °C. The average SEC was 0.97 kWh/kg. Because of the progressive reduction

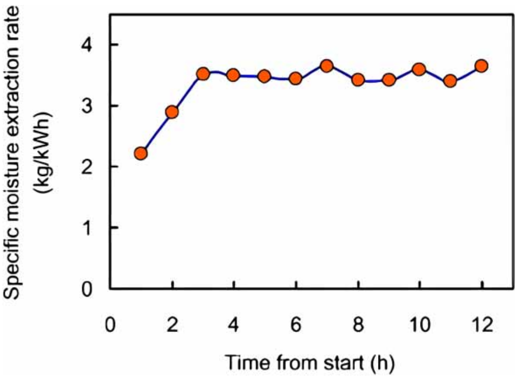


Figure 10 | Specific moisture extraction rate (SMER) for the example drying run.

of the recirculating exhaust air's water vapor content, the batch dryer's energy efficiency decreased during drying, which is why the SEC reported, averaged over the entire batch drying duration, exceeds that in this study.

In contrast, several groups have reported energy performance data for sludge drying by combustion-heated dryers. Table 2 summarizes the SEC data reported in four studies. They are in the range 0.865–4.3 kWh/kg, where kWh refers to the sum of the fuel and electricity consumptions. These values are much larger than the values of 0.28–0.36 kWh/kg reported in this study. However, these relatively large SECs are less important economically if waste heat can be used as the thermal energy source or the dried product can be used as fuel.

Table 2 | SEC data for sludge drying by combustion-heated dryers

Sludge source	Energy source	Operating mode	SEC (kWh/kg)	Reference
Paper mill activated sludge plant	Hot gas from coal combustion	Batch	1.11–1.33	Avelar *et al.* (2019)
Sewage treatment plant	Waste heat from dried sludge combustion	Continuous	$<$0.865	Geraats *et al.* (in press)
Pulp and paper mill activated sludge plant	Hot air from wood pellet combustion	Continuous	1.9–4.3	Mäkelä *et al.* (2017)
Recycled paper sludge from pulp and paper mill	Hot air from wood chip/pellet combustion	Continuous	1.5–3.1	Mäkelä *et al.* (2014)

Comparison of dryer energy performance might be more meaningful if the processes considered used the same energy source. Thus, it is interesting to compare the heat pump dryer in this study with electrically heated dryers. One such dryer type uses microwave heating. Microwave heating's potential for sludge drying has been explored in several studies (Idris *et al.* 2004; Chen *et al.* 2014; Bennamoun *et al.* 2016; Lee *et al.* 2018; Yenikaya *et al.* 2018; Tınmaz Köse *et al.* 2019). Because microwave heating SECs are scale dependent (Bermúdez *et al.* 2015), appropriate energy performance data must be selected so that a fair comparison can be made with this study's results. Work by Mawioo *et al.* (2017) is useful in this respect as its SECs are deemed accurate on the basis of criteria proposed by Bermúdez *et al.* (2015). Mawioo *et al.* (2017) employed a pilot-scale microwave process to batch dry different types of sludge. The SECs for this system were in the range of 2.8–4.6 kWh/kg, considerably higher than the range of 0.28–0.36 kWh/kg reported in this study. This implies that heat pump drying is more energy efficient than microwave drying. Mawioo *et al.* (2017) suggest that several factors contributed to the microwave system's comparatively low efficiency, including sup-optimal condenser performance, poor reactor insulation, and harsh operating conditions. Batch drying is generally less efficient than continuous drying, too.

The heat pump dryer used in this study proved generally efficient and effective. Although heat pumps are starting to be used for industrial sludge, they are little used in China as there is little experience in the municipal sewage sludge sector, which is dominated by combustion-heated dryers. Open-cycle combustion-heated drying plants must deal with air pollution issues – for example, emissions of dust, malodorous gases, and volatile compounds. There are also serious concerns about safety aspects because such dryers operate at relatively high temperatures. Heat pump dryers work in closed environments at lower temperatures, which mitigates these issues. Despite these advantages, heat pump drying is not yet viewed as a mainstream technology for sewage sludge, probably largely because of lack of awareness. Nonetheless, these benefits seem likely, eventually, to help spur significant adoption of heat pump drying in China's sewage sludge sector – an enormous market (Yang *et al.* 2015; Lu *et al.* 2019; Cao *et al.* 2020).

CONCLUSIONS

This paper includes the design details and sludge drying results for a belt dryer based on heat pump technology. To increase its efficiency, the dryer incorporated a 3-in-1 apparatus in the refrigerant circuit and a recuperator in the recirculating air circuit. The temperature of air entering the drying chamber – maintained at 65 °C by rejecting surplus heat via external condensers – was used as the thermal control parameter. An example run showed that the dryer performed satisfactorily when the initial sludge moisture content was <82% and the residence time 120 minutes. The final sludge moisture content from the dryer was <13%. The average MER, which indicates dryer capacity, was 178 kg/h. Because the heat pump system is modular, capacity can be increased easily by adding more modules and increasing belt length. The SMER, an indicator of energy efficiency, was 3.5 kg/kWh. This comparatively high value suggests that the heat pump dryer is more efficient than combustion-heated dryers. However, because heat pump dryer operating temperatures are lower than those of combustion-heated dryers, drying times are likely to be longer. In summary, heat pump dryers offer advantages like high energy efficiency, safe and reliable operation, low environmental impact, and ease of use when drying industrial wastewater sludge.

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