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Air source heat pump assisted drying for food applications: A mini review

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ABSTRACT

Drying as one of the oldest food preservation processes is also the most energy demanding process. Nowadays, when conventional energy sources are declining, reduction/rationalization of energy consumptions in industrial processes is of great importance. One of the more successful ways of saving energy and make the process energy efficient is the integration of heat pumps within the existing technological processes. Heat pump systems are successfully used for different applications such as heating and cooling, and drying as well. In addition, the quality of final dried product is a priority that can be accomplished by heat pump assisted drying systems. This paper presents up-to-date survey in the field of air source heat pump assisted drying of food: fruit, vegetables, herbs and spices.

Introduction

The way of extending the food lifetime by water removal is known and has been widely used since ancient times. People exploited the heat of the sun, the fire, as well as the airflow, to remove water from food, of either plant or animal origin. So are dried and preserved venison and fish, and later on the fruits of various plants (fruit, peppers, various roots, potatoes). This way of conserving food is mentioned by Romans, Greeks (Pericles), Chinese, Indians and others. Known techniques of water removal were also applied to concentrate liquid foods, the preservation of fruit in honey and the like. Even today, in the Middle East, the Mediterranean and California there are still serious quantities of produced, on the sun dried, foods (Tiwari et al., 2016). The food preservation by drying developed rapidly and reached industrial proportions in the United States in second half of the I World War. Since the 1950s, extremely fast development of industrial drying and concentration of liquid foods has been register. From then on, intensive efforts have been made to improve the existing and find new technologies with an emphasis on the energy efficiency of the process since it is commonly known that drying is one of the most energy-intensive unit operations. Over 33% of primary energy sources are used for industrial drying (Minea, 2013). It is important to point out that energy efficiency should not be look on as energy savings because the energy savings imply a certain renunciation that energy efficiency is not. Efficient use of energy never disrupts working and living environment. According to the International Energy Agency (https://www.iea.org/topics/energyefficiency/) energy efficiency is often defined as achieving the same services with less energy. This definition grossly understand the power of energy efficiency to provide benefits beyond energy savings for society and for the economy.

Part of the energy consumed in the process consists of losses that can be caused by: losses of industrial processes, power grids, equipment, poorly run and waste heat. Major of the energy losses in the drying process are waste heat that has a negative impact on production efficiency and on environmental as well. Drying causes a considerable thermal load of the environment through waste heat, which is released from the process. Exploitation of waste heat leads to the above-mentioned energy efficiency of the process

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along with financial benefits and lower environmental burden. Good results in the recovery of waste heat were achieved by using heat pumps. The heat pumps feature a high level of energy efficiency and the ability to operate independently of external conditions.

According to the heat transfer mechanisms during drying the conventional drying techniques involves convection, conduction and radiation, whereby in industrial practice over 85% refers to convective dryers. The heat transfer medium used in such dryers are usually hot air or combustion gases (Moses et al., 2014). Therefore, the examples of air source heat pump assisted drying for food applications will be summarized in this paper.

Heat pumps

Heat pumps use free thermal energy from the ground, groundwater or air and transfer heat to the final consumers through the heating system. Additionally, during the summer months heat pumps are used for cooling. Heat pumps do not produce harmful gases and work very efficiently even at low ambient temperatures. The system is easily applied to existing installations and in this way, it is possible to provide heat for final consumers.

For domestic and/or industrial applications, the following types of heat pumps are used:

- Vapor compression cycle
- Absorption cycle
- Thermoelectric heat pump

The most commonly used, of the above, is the compression vapour cycle due to its yields a high-energy efficiency. The vapor compression heat pump cycle is presented in the Fig. 1. There are various designs of heat pumps for various applications, but the basic components of the system do not differ: evaporator, compressor, condenser, expansion valve, and refrigerant.

How does heat pump work?

Heat pumps have been successfully used for many years for different applications, such as heating and cooling systems (Ahmadi et al., 2018), and in drying technology (Babua et al.,2018; Jin et al., 2017; Lamidi et al., 2019).

The heat pump system may divided into three circuits (Fig. 1.):

I. Collecting thermal energy from the surrounding
II. Raising the temperature
III. Transfer of produced heat further

The air, contain the certain amount of heat, is supplied to an evaporator in which a refrigerant flows inside the tubes. The refrigerant temperature inside the evaporator tubes is always lower than the temperature of air. The difference in air-refrigerant temperatures allows heat exchange. The air transfers its heat to the refrigerant that is used it for evaporate. The generated vapour is further sucked by the compressor, whereby during compression is increased the pressure and temperature of refrigerant vapour. The temperature of the vapour at the output from the compressor can reach up to 80 °C, depending on the characteristics of the compressor. The refrigerant at the outlet of the compressor is at the pressure that is corresponded to the temperature of condensation. In the condenser, the vapour of refrigerant exchange the heat with the air or water that is further used for heating (industrial and/or domestic) and cool down to the condensation temperature. The refrigerant vapour condenses to the liquid state but still relatively high temperature. As such, the refrigerant is not ready to start the cycle from the beginning and take over the heat from the surrounding air. Further, flowed through the expansion valve that decreased the pressure and temperature of liquid refrigerant, which corresponds to the condensation pressure and temperature. After that, the cycle start from the beginning.

If the heat pump is incorporated into an existing hot air drying system, the heat contained in the exhaust warm moist air (latent and sensible heat) can be utilized. Thereby reduce the consumption of fuel consumed for the heating of air or electricity used by the heater, to increase the energy efficiency of the process and reduce the thermal load of the environment by hot and wet air from the dryer. In addition to the above, with heat pump the precision control of the temperature and humidity of the drying air is possible. The air temperature and humidity are one of the most important parameters in drying process since the main task is to produce high quality products. For this reason, heat pump assisted drying systems have found their applications for drying of high heat-sensitive foods (e.g. fruit, vegetables, spices) and fine chemicals in pharmaceutical industry.

The most commonly used industrial dryers are hot air dryers where the drying material is brought into direct contact with the heat transfer medium. This is the so-called convection drying. The most widespread is the one-time airflow, whereby the material is dried in airflow in one pass through the drying chamber, which because of the relatively high air temperature adversely affects the drying material.

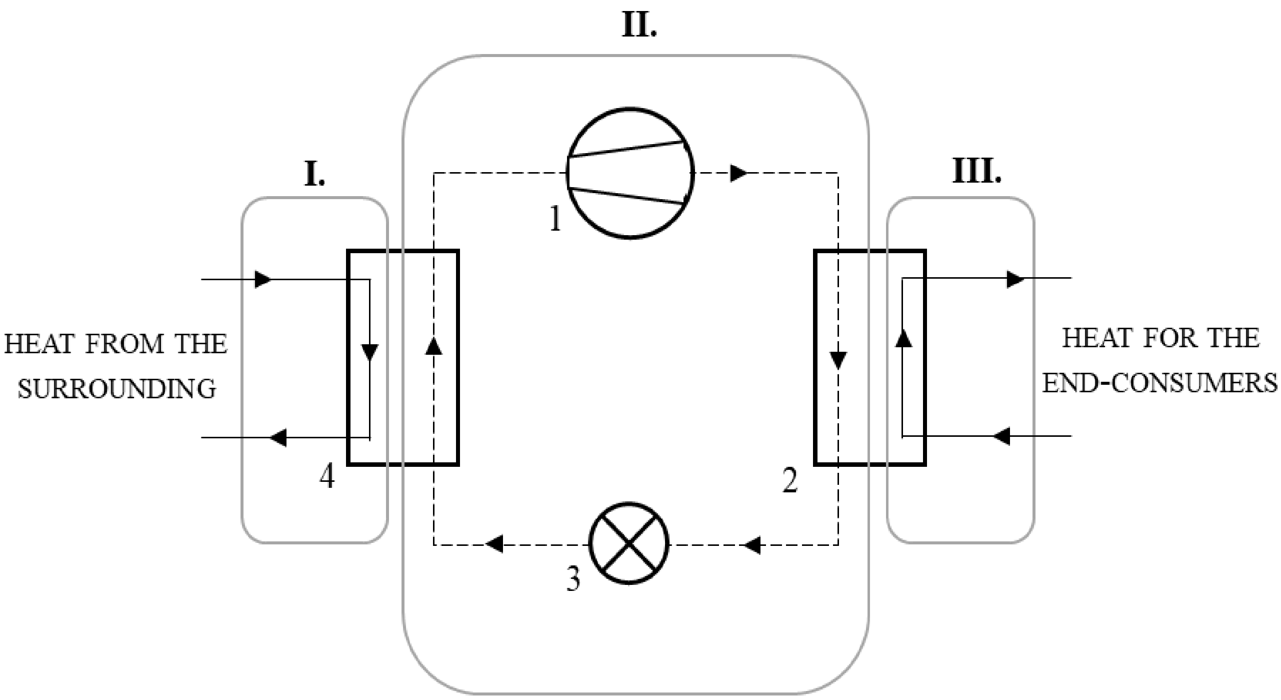

Fig.1 Schematic presentation of heat pump (1 compressor, 2 condenser, 3 expansion valve, 4 evaporator)

Since food (fruits, vegetables, spices) is dried most often in hot air dryers, sometimes the products obtained do not comply with strict qualitative regulations in terms of flavour, colour and shape. Another negativity, apart from the high temperature of drying air that negatively affects the physico-chemical properties of food, is the release of hot air from the dryer directly into the environment. All these drawbacks can be avoided, as already mentioned, by implementing of heat pumps into an existing conventional drying process. This not only increases the energy efficiency of the process but make possible to take the drying process at a lower temperature, which ultimately results in a better quality product.

Heat pump dryer

With regard to the application, the basis of the drying process with the implemented heat pump can be different in design. Fig. 2. is shown a scheme of a conventional drying process with hot air upgraded with a heat pump operating with bypass of airflow. In the process, besides the basic units of the heat pump, heat recovery unit (recuperator) is included. In the heat recovery unit, the heat contained in the warm moist air on the outlet of the dryer is utilized to preheating the air before entering the condenser. The condenser serves as a heater while on the other hand the evaporator serves as a dehumidifier.

The most commonly used heat pump systems are closed-loop systems that in a thermodynamic point of view based on the principle of Carnot circular process. The heat pump dryer has the ability to transfer the latent heat of condensation as the sensibly heat onto air that is introduced in the condenser (Fig. 2.).

The most important advantages and disadvantages of heat pump assisted dryers can be summarized as follows

Advantages:

- High energy efficiency by exploiting waste heat;
- Efficient temperature and humidity control of the drying air;
- Low drying temperatures;
- Suitable for drying at the temperature of sensitive foods, agricultural products and fine biomedical chemicals;
- Drying takes place regardless of low ambient temperature;
- Reduction of total energy consumption in the process (electric and fossil); and
- A short pay-back period.

Disadvantages:

- High initial investment and high maintenance costs (compressor maintenance);
- Requires additional space;
- A more demanding process;
- Requires trained workers; and
- Potential risk of leakage of the refrigerant.

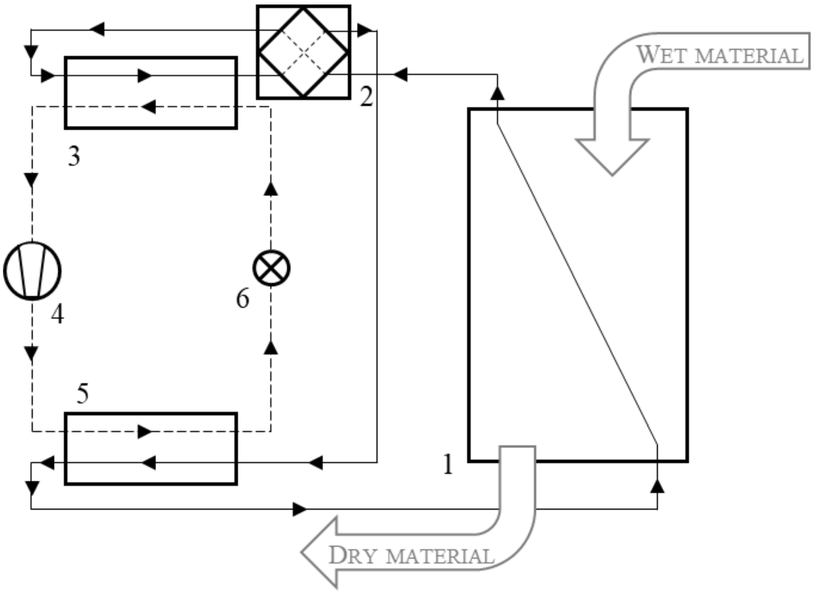

Fig. 2 Schematic presentation of air source heat pump assisted drying (1 drying chamber, 2 heat recovery unit, 3 evaporator, 4 compressor, 5 condenser, 6 expansion valve)

Air source heat pump dryer

Published articles in the area of assisted drying heat pump can be roughly classified, in relation to the topics they deal with, as follows: (i) Articles dealing with energy efficiency and economic viability of the drying process. (ii) Articles dealing with the development and validation of the models associated with the drying process. (iii) Articles dealing with the study of qualitative parameters (physical as colour and shape, and chemical as nutritionally high-value compounds and volatile aromatic compounds) of dried products.

In the Table 1. the study criteria of selected published articles regard to air source heat pump assisted drying of agro-food products are presented. Generally, heat pump assisted drying allows the drying of materials at lower temperatures than is possible and commonly in case of hot air drying (Table 1.), where temperatures up to 90 °C are used (Sunthonvit et al., 2007; Ong et al., 2012). This gives advantage to heat pumps assisted drying over conventional drying with hot air. According to published scientific studies, in spite of the longer drying time (up to 1.5 times longer) (Lee and Kim, 2009) that is inevitable since the drying temperatures are lower when heat pump are employed for the equal amount of water removal, the energy efficiency of such drying is greater than in the conventional manner. Heat pump dryer need less energy to achieve the same goal. Through experimental work, Lee and Kim (2009) who investigated the energy savings and efficiency of batch-type heat pump dryer in comparison with hot air dryer have proved this. The study shown that with batch-type heat pump dryer is possible to save 59 – 70% of energy that is required for conventional drying with hot air dryer. The authors especially for this purpose designed and constructed the dryer based on the simulation of the heat pump cycle and the drying process. Researches were carried out and confirmed on drying of shredded radish. Taşeri et al. (2018) are reported that with open-loop laboratory heat pump dryer is possible to reduce the energy consumption, in comparison to the convective dryer, up to 51% with additional reduction up to 3% with increasing in air velocity from 1.5 to 2.5 m/s. Drying were conducted for grape pomace at 45 °C. Moreover, increasing in air velocity besides the additional energy consumption reduction reduces the drying time up to 69%. The maximum drying rate were recorded at air velocity of 2.5 m/s, while the smallest loss of bioactive properties was recorded at an air velocity of 2.0 m/s. The heat exchange between the air and the heat pumps depends largely on the speed and mode of air flow: the open, half-open and closed air circulation system. Liu et al. (2018a) explored the open, semi-open and closed type of air source heat pump assisted drying. The closed system was studied considering the different bypass air rates: 0, 0.2, 0.4, 0.6, 0.8 and 1. In addition, the influence of ambient air conditions on all three types of drying was monitored: a minimal (T = 2.4 °C, ϕ = 76%), a maximal (T = 27.8 °C, ϕ = 81%) and an average (T = 15.4 °C, ϕ = 76%) air temperature and humidity. As expected, the closed system is most stable with regard to the conditions of surrounding drying air but most affected by the bypass air rate.

Table 1. Research criteria in the air drying process assisted by heat pump of agro-food products

Agro-Food Products				**Drying air**			**Duration time, min**	**References**
Type	**Shape**	**Initial moisture content, (%)**	**Final moisture content, (%)**	**Temperature, (°C)**	**Humidity, (%)**	**Velocity, (m/s)**		
White radish	slice 10x10 mm with arbitrary length	95 (w.b.*)		40				Lee and Kim, 2009
Plum	uniform slice: 4.0 ± 0.5 mm	84.5±1.1 (w.b.)	10.4±1.5 (w.b.)	45, 50, 55	10	1.5		Erbay and Hepbasli, 2014
Apple Potato Banana	cubes: 10x13 mm chips: 2x3 mm cylinders: 6x7 mm			35, 45, 55	10, 20 and 30	1, 1.5 and 2		Zlatanović et al., 2017
Carrot	chips 3 mm tick							Shengchun et al., 2018
Grape pomace		2.57 (d.b.**)	0.1 (d.b.)	45		1.5, 2.0, 2.5	1 040 (1.5 m/s), 840 (2.0 m/s) and 720 (2.5 m/s).	Taşeri et al., 2018
Garlic	chips 3 mm tick							Liu et al., 2018a
Figs	uncut			46.1 – 60		1.0 – 5.0		Xanthopoulos et al., 2007
Ginger								Phoungchandang and Saentaweesuk, 2011
Sweet basil leaves			10.34 (w.b.)	40, 50, 60		0.5		Phoungchandang and Kongpim, 2012
Tomato slices	7 mm tick, 40 mm diameter			35, 40, 45		1		Coşkun et al., 2016
Tomato	pulp		6 – 7 (d.b.)	40		1.71		Jayaprakash et al., 2016
Sliced pineapple								Tunçkal et al., 2018
Rough rice								Harchegani et al., 2012
Nectarine	0.5 mm thick slices		18 – 20 (w.b.)	25, 60	10	1.6	1 140	Sunthonvit et al., 2007
Olive leaves		49 (w.b.)	5.17 – 20.27 (w.b.)	45 – 50		0.5 – 1.5	270 – 390	Erbay and Icier, 2009
Parsley, spearmint, Jew's mallow			6 (wb)	45. 50. 55		1.2, 1.9, 2.7		Fatouh et al., 2006
Pear, Apple, Papaya, Mango	cubes:15 mm		4.8 – 16.6 (d.b.)	35	20		840	Chong et al., 2013
Onion shreds	2 mm thick			35, 40, 45, 50	32, 26, 19, 15	2		Sahoo et al., 2015
Salak friut	40x20x3 mm		19 – 13 (d.b.)	26 37	27 17		180 720	Ong et al., 2012
Sweet pepper	0.5 cm thick slices			30, 35, 40	40, 27, 19	1.5	1 440	Pal and Kan, 2010
Gac Fruit Pulp	5 mm thick slices			40-60		0.5		Tirattanapikul and Phoungchandang, 2016
Gac peel				30 40	30 40			Chuyen et al., 2017
Chestnuts		48 – 50 (w.b.)	7 – 11 (w.b.)	25 – 30		5	40 260	Giovenzana et al., 2013

Table 1. Continued

Agro-Food Products				Drying air			Duration time, min	References
Type	Shape	Initial moisture content, (%)	Final moisture content, (%)	Temperature, (°C)	Humidity, (%)	Velocity, (m/s)		
Garlic	1 mm and 2 mm tick slices	1.63 – 1.88 (d.b.)	0.06 (d.b.)	37 – 40	3 – 5	1	600 – 780	Aware and Thorat, 2011
Apple, Blueberry (wild/cultivated), Raspberry, Chokeberry, Morello pomaces				45		1.5		Brushlyanova et al., 2013
Macadamia nuts			8 (d.b.)	38 – 40	14	1.71		Phatanayindee et al., 2012
Coffee beans			11 (w.b.)	50	70	2	4 320	Dong et al., 2017
Cocoa beans				28.2 40.4 56.0	56.7 18.1 14.6	4.6		Hii et al., 2012
Lentinula edodes (shiitake mushrooms)				35 – 62		2 3	1 020 1 200	Liu et al., 2018b

*wet basis; **dry basis

The best results, the maximal specific moisture extraction rate, were achieved when the bypass air rate was 0.4 hence the most energy efficient. Since the process parameters of air source heat pump dryer can be precisely controlled or/and optimized, the reduction of energy consumption in all three studied drying systems can be achieved by air with low humidity and high enthalpy at the condenser inlet. Shengchun et al. (2018) were investigated the effect of drying air temperature (30, 35 and 40 °C) and air flow ratio (0.4, 0.6, 0.8 and 1) for drying of 3 mm thick carrot chips in enclosed heat pump dryer system with auxiliary condenser and air bypass. According to their study, increasing an air temperature decrease drying time and the energy consumption by compressor. At a drying temperature of 40 °C with an air flow ratio of 0.6 drying time and energy consumption decreased by about 15% each. Zlatanović et al. (2017) were designed and constructed the laboratory air source heat pump dryer. The drying process was carried out with full air recirculation. Energy efficiency was estimated according to the parameters: heat pump dryer efficiency, moisture extraction rate, specific moisture extraction rate and specific energy consumption. According to their results, the best system is turned out to be the one with partial recirculation of air. A pilot scale heat pump conveyor dryer for food was designed and constructed by Erbay and Hepbasli (2014). Conventional and advanced exergoeconomic analysis were applied to analyse the contribution of each components of the drying system (compressor, expansion valve, heat recovery unit, condenser, and evaporator) at different drying air temperatures. The recuperator proved to be the most important component of the heat pump dryer with regard to the accumulation of costs. As the previous study shows (Shengchun et al., 2018) Erbay and Hepbasli also concluded that lower costs and greater energy efficiency could be achieved by increasing the inlet air temperature. Ji et al. (2017) were carried out the drying of chili in a specially designed heat pump dryer with a two-temperature level. The effect of the drying temperature (first and second level) and the thickness of the material layer on unit energy and time consumption during drying was studied and optimized by response surface methodology. The best results were achieved when the temperature in the first stage of drying was 48 °C, in the second 61 °C with a thickness of 44 mm in 896 minutes, where the 92.05 kJ / kg was consumed.

Especially designed and constructed heat pump dryer on hot air for energy consumption and quality of rough rice drying process investigation was based on numerical simulation (HYSYS software). The numerical simulation were conducted by newly developed non-equilibrium model (MATLAB software) by Harchegani et al. (2012). The total power consumption by fully closed loop heat pump dryer system was reduced about 10% and fissure kernels value about 40%. The thin-layer models were used (Tunçkal et al., 2018; Coşkun et al., 2016; Phoungchandang and Kongpim, 2012; Phoungchandang and Saentaweesuk, 2011; Xanthopoulos et al., 2007) to fit the experimental data collected during drying (closed heat pump cycle for all reported studies) of different kind of food (pineapple, tomato slices, sweet basil leaves, ginger, and figs) by means of non-linear regression analysis. Of the 25 mathematical models tested for the fit of experimental data, the best were Midilli et al. and Agbashlo et al. (pineapple and tomato slice); Parabolic (tomato slice); Henderson (sweet basil leaves); modified Halsey, modified Oswin and modified Page (ginger); and Logarithmic (gifs) models.

Fruit and vegetable drying methods should primarily be in the service of the final product quality. For that reason, the largest number of papers published on the topic of heat pump assisted drying aim to investigate the degradation of quality properties after drying. Most of the papers (Pal and Khan, 2010; Sunthonvit et al., 2007; Erbay and Icier, 2009; Fatouh et al., 2006; Sahoo et al., 2015; Ong et al., 2012; Chong et al., 2013; Jeyaprakash et al., 2016) indicate that the air source heat pump assisted dryer is the best technique for drying fruit (nectarines, salak, apple, pear, papaya, mango) and vegetables (onion shreds, tomato), herbs (parsley, spearmint, Jew's mallow, olive leaves) and spices (sweet pepper) as very sensitive materials, due to low temperatures of drying that can be achieved. By studying the effect of the drying method on the content of carotenoid and antioxidant activity after drying Gac fruit, two groups of authors came to the opposite conclusion. Trirattanapikul et al. (2016) have concluded that for Gac fruit pulp the best method, the one that most preserves carotenoids and after which the least antioxidant activity is reduced, is heat pump assisted drying at 60 °C. On the other hand, Chuyen et al. (2017) are recommended for drying of Gac peel hot air drying at 80 °C and vacuum drying at 50 °C for preservation of carotenoids and antioxidant activity. As far as we know, it is the only article that puts other drying method(s) in front of assisted drying by a heat pump. Quality parameters such as bioactive components, fatty acid content, non-volatile and volatile aromatic compounds the most remain preserved by heat pump assisted drying process (Giovenzana et al., 2013; Phatanayindee et al., 2012; Dong et al., 2017; Hii et al., 2012). Aware and Thorat (2011) have confirmed their hypothesis that by drying garlic at low temperatures (37-40 ° C) in a heat pump dryer the final product will be better quality. The higher allicin retention, up to 94%, was recorded by drying the garlic slices 2 mm tick. Considering all the known advantages of heat pump assisted drying, Liu et al. (2018b) have investigated the possibility of applying to the drying of a shiitake mushroom. Traditional drying is carried out in convection driers by hot gasses obtained by combustion of coal, thus significantly load the environment. The experiments were carried out in a air source heat pump dryer especially constructed for drying a shiitake mushroom at a temperature range of 35-62 ° C. The product obtained has been well suited to the quality of traditional dried mushrooms. The authors therefore emphasize that the method should be applied more widely.

Conclusions

By literature review, it is apparent that the air source heat pump assisted drying in comparison to other drying methods are in favour because they are energy and economically more efficient, which reduced fossil fuel consumption and most importantly the final products are of equal or better quality than conventional dried products. The real challenge will be to achieve the full potential shown by air source heat pump assisted drying systems. The room for improvement always has - conventional heat sources can be replaced by unconventional ones such as solar energy, for primary heating of the drying air.

To make the drying process with implemented heat pump reliable and simple on the industrial level it should be invested in interdisciplinary research that will involve not only the academic community, but also the valuable knowledge and experience of engineers from the industry.

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