UTILISATION OF LOW-TEMPERATURE HEAT IN AGRICULTURE USING HEAT PUMPS - CURRENT STATE AND PROSPECTS

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Abstract. The work presents in a synthetic way available results of the research on utilisation of heat pumps in agricultural production. Moreover, on the basis of multiannual average values, the researchers calculated potential possibilities for storing waste heat, which may be reused in a typical tomato-growing greenhouse.

Key words: heat pump, greenhouse, waste heat

Introduction

When analysing various issues (also those energy-related), one should take into account factors affecting natural environment. There are many examples, where once disregarded factors caused environmental damage, e.g. insecticidal agent - DDT, pesticides, freon, improperly carried out agricultural drainage, excessive fertilisation, arable crop monocultures, and many other. Analysis covering recent years proved exponential (abrupt) relationship between the volume of energy being consumed and mass of combustion products emitted into the atmosphere. Admittedly, natural sources of non-renewable energy (coal, petroleum, gas) will still last for another few generations, however natural environment will neither absorb nor regenerate by-products formed during production and combustion products (dust, nitric and sulphur oxides, and carbon monoxide). Hence, many scientific centres carry out intensive research on using renewable heat sources (river, wind and solar radiation energy, geothermal energy, or biomass) for energy purposes. Cyclically held international conferences are dedicated to current use of renewable heat sources. Thus, a report on geothermal energy utilisation in the world was presented during World Geothermal Congresses [Lund et al. 2005]. On the basis of data gathered by 72 countries, the researchers estimated energy production at the level of 273.3 TJ·year^{-1} (75.9 GWh·year^{-1}) – 43% increase compared to 1995. Geothermal energy was used for: current operation of heat pumps (32%), heating in pools and bathrooms (30%), heating in the other rooms (20%), heating in greenhouses (7.5%).

These studies include many works analysing heat pump utilisation for energy purposes. Thus, the purpose of the work is to present current state of knowledge and to indicate the future concepts for using heat pump for energy purposes.

Results of some research works in the scope of heat pumps utilisation

Below, some operating aspects of systems using heat pump are discussed on the basis of available literature.

Berntsson [2002] presented usability analysis for lower sources working with a heat pump, divided into investment outlays, ecological and energy effects, and work efficiency. Then, on the basis of experimental research, Huang and Lee [2007] presented a correlation model between heat pump energy effects and decision-making parameters affecting efficiency of this system and energy efficiency coefficient. The results of computer simulation carried out using a mathematical model of energy effects were demonstrated by Chen et al. [1997].

Apart from the discussed issues, some researchers analysed lower heat source type. And so, research results, where surrounding air was used as a lower heat source, were presented by: Xu et al. [2006], Kaygusuz and Ayhan [1999], Hawlader et al. [2001], Kaygusuz [1995], Huang and Cheng [2001], and Nicholls [1981]. In their experiments, the authors were using heat to heat up: process water, liquid stored in an energy accumulator, and the bed that was subject to phase transitions. Completed experiments allowed to determine the system energy efficiency (COP - Coefficient of Performance) and energy effects (accumulated energy volume).

Soil was another analysed lower heat source type. Results of the research on energy efficiency, unit output of exchangers (both horizontal and vertical), their spatial configuration and type, the impact of ground water level and outside conditions on COP value, economic aspects, and verification of mathematical model describing space-time temperature changes in soil, are contained in the following works: [Nagano et al., 2006; Omer, 2006; Hepbasli et al., 2003; Ozgener and Hepbasli, 2005a, 2005b, 2005c; Yang et al., 2006, Esen et al., 2006; Składzień et al. 2002; Inalli and Esen, 2004; Fic et al., 2003; Kurpaska and Latała 2008a].

The COP value, comparison of energy effects obtained when using heat pump and combustion of non-renewable carrier, reduction in the volume of deleterious substances emitted into the atmosphere as a result of using heat pump in the system, mathematical model describing functioning of the entire system (heat pump, lower and upper source), analysis of a hybrid system (solar collectors heating up medium constituting lower source for heat pump) in which water was used as a lower source, were all analysed by: Kaygusuz [2000], Yumruta and Unsal [2000], Aye et al. [2002], Trillat-Berdal et al. [2006a, 2006b], Baek et al. [2005], Zeng et al. [2003], Renedo et al. [2006], Gan et al.[2007], Kurpaska and Latała [2008b]. The researchers analysed various forms and usability of water available in natural environment as a lower heat source: surface waters, ground waters, deep waters, and sewage plant effluent.

Moreover, available literature includes works analysing different ways of using a heat pump. Research results were given by: Kuang and Wang [2006], Chou et al. [2004], Riffat and Gillott [2002], Soylemez [2006], Nowak et al. [2006], Argiriou et al. [2005], Kurpaska [2008]. The authors were determining COP value, finding optimal values of decisive variables, examining energy-ecological-economic aspects for using heat pump to: heat up residential buildings, heat up garden facilities, reduce air humidity inside a facility during its ventilation, cooling, and seeds drying.

Analysis of electric energy consumption to run components of the system, in which heat pumps were used to heat up water, are contained in the following works: Huang and Lee [2004], and Morrison et al. [2004].

Utilisation of heat pumps in agriculture, including some research results

Available literature specifies reasons confirming profitability of using heat pumps in installations. The most important of them include:

– existence of heat source characterised by relatively high temperature (preferably higher than ambient temperature), yet insufficient for direct use,
– employing a heat pump allows to turn back and reuse energy stream flowing through the system (e.g. in air conditioners),
– occurrence of demand, both for heat and cold,
– the case, in which heat is transmitted over long distance, where a heat pump installed at energy consumption point would reduce capital costs.

The quoted reasons provide grounds to state that these conditions seem to be easy to meet in agricultural production. This is the case when heat pump may be used in an alternative configuration, both for heating and cooling purposes, and also when there is a possibility to utilise waste heat. Moreover, there is a whole range of processes in agricultural production, where the sources of recoverable waste heat include: heated up humid air leaving drying plants, cooled agricultural products (milk, fruit, vegetables), ventilation air carried away from facilities, which have to be provided with proper humidity (livestock buildings, covered garden facilities), animal excrements in solid form (manure dung) and liquid (e.g. from liquid manure pit).

As a result of employing a heat pump, recovered heat may be used for the following purposes: process water heating (water for irrigation, water used in production processes), air heating and drying in drying plants, heating ventilation air supplied from outside into production rooms, direct heating in production facilities (e.g. greenhouses, foil tunnels), processes in agricultural and food industry.

There are some solutions, in which heat pumps have been employed in animal and gardening production, and in agricultural and food industry. And so, studies carried out by Nawrocki and Myczko [1998] proved that as a result of installing a ground exchanger (constituting lower heat source for pump) in swine fattening farm on the so-called deep bedding (four pens sized 4.5×19 m and livestock density 80 animals per each pen), in autumn-winter season it would be possible to heat amenity room sized ca. 40 m^2 up to the temperature of 18-21°C, and to obtain hot water without deteriorating zootechnical conditions in rooms. Kupczyk and partners [2001] presented experimental results for using heat pump to recover waste heat during milk cooling process. Completed studies allow to observe that while cooling milk from initial temperature of 35°C down to 5°C, when acquiring 1000 l of milk at one time, pump characterised by heating power 12.2 kW and power consumed by compressor motor 2.7 kW reaches COP value ca. 4.5. The authors have calculated that in this way it is possible to recover from cooled milk more than 34 GJ of heat per year. Two-stage water heating methods (pump with an additional heat source) are employed in all cases where it is needed to obtain higher heat receiving unit temperature. The following values are assumed to constitute profitability threshold for installing a device working according to heat pump principle: 150 litres of milk per 1 milking, accumulated in tanks with capacity ca. 500-600 l.

Completed experimental studies on utilising heat pump to heat up garden facilities [Kurpaska 2008a, 2008b] allowed to prepare nomograms for determining basic operating parameters of a monovalent and bivalent system. Nomograms were developed for a tunnel with usable area 54 m^2, in which a heat pump (rated heating power 9.7 kW) was installed. Vertical and horizontal ground heat exchangers characterised by diversified supply (vertical exchangers: U and 2U), and also single, double and spiral exchanger (horizontal ones) were used as lower heat source. In a bivalent system, the research was carried out at the following configuration: solar collectors (flat-plate and vacuum-tube) – accumulating tank (with diversified water capacity) – lower source for heat pump.

Intensive research works on utilisation of heat pumps are carried out especially in food products processing industry. Extended review of obtained research results and technical solutions was delivered by [Paliwoda 2001]. When making a synthetic division of analysed works, the author divided heat pump applications as follows:

– heating up water for process and hygienic-sanitary purposes, and heating up products at different processing stages. Heating-cooling pumps are used here (pumps, which carry out heating and cooling process at the same time). In these installations carbon dioxide is used as working medium in a heat pump system (compressor-condenser-evaporator). An important advantage of the presented system is the possibility to obtain water temperature reaching even 90°C. Although, this extorts using high compression pressure values (almost 105 bar) and thus high power of electric motors driving compressors. However, detailed tests conducted at a test stand: pump heating power 130 kW; process water heating possible up to 90°C; cooling power 90 kW; compressor driving power 50 kW, have proven that if heating process is carried out simultaneously with water cooling, it is possible to reach COP value exceeding 5.
– concentrating solutions (by evaporating water fraction). There are many food products not resistant to high temperatures, since they are subject to denaturation processes. In these cases, concentration processes have to proceed at lowered pressure conditions, and as a consequence at reduced water fraction evaporation temperature. In one of possible technical solutions, vapours carried away from evaporator are lower heat pump source for evaporator. Compressor draws in medium vapour (usually ammonia – NH_3, or CO_2) from evaporator, compresses it and forces into condenser, which heats up concentrated solution. Due to vapour condensation, pressure value drops below atmospheric pressure, as a result of which water fraction evaporation may take place at low temperature (usually within range 20 to 50°C). Operating tests have proven that in the presented system Coefficient of Performance (COP) value ranges from 6 to 8.
– convection drying of moist food products (both loose and ground). Compared to conventional heating (heat generated during fossil fuels combustion, drying with atmospheric air), heat pumps employed in drying technology allow to obtain higher final quality of product subject to drying, better utilisation of raw material, reduction of its losses, decrease in energy consumption due to high COP value (ranging from 4 to 5). Sometimes, CO_2 is used as pump working medium, which ensures ecological neutrality, both towards product subject to drying and environment. Operating tests carried out for fluidisation drying plant, in which the researchers installed a heat pump, have proven

that there is almost 380% increase in drying intensity efficiency, while maximum operating efficiency per unit energy consumption is 4.7 kg of evaporated water per 1 kWh.

Summary and further research prospects

There are forecasts that in 2020 the share of geothermal energy (including also heat pumps) in general renewable energy balance will increase from current 1.8 to almost 3.1%. Therefore, there is a need to intensify studies in this field. One of potentially possible ways for increasing heat pump operation efficiency is to ensure higher temperature of lower sources. It is possible for example in case of production carried out under covers, which potentially allows to accumulate heat surplus in the summer season. Fig. 2 presents the average multiannual weather conditions for Warsaw, with marked heating and cooling seasons in a typical greenhouse. As it can be seen then, there are periods of several dozen days, during which it is possible to utilise surplus heat and to transfer this surplus to an accumulator (in case of energy surplus) and to recover this energy (during higher heat demand periods). Heat recovery using a heat pump is the most advantageous. Thermodynamic analysis indicates that the higher temperature of lower heat source, the lower theoretical unit compressor work (lower power for compressor driving). Increase in cooling effect unit value occurs as well, and as a consequence also unit thermal effect of condenser. Finally, the COP value grows.

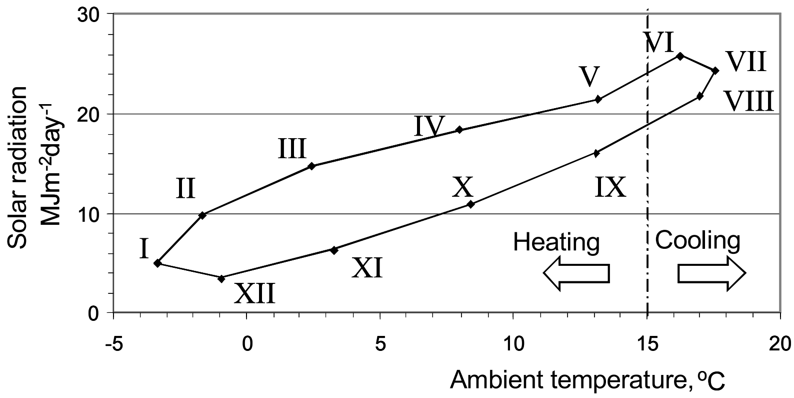
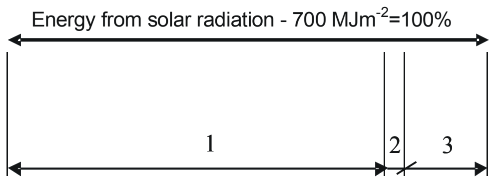


Fig. 1. Average climatic conditions for Warsaw

Fig. 2 presents results of theoretical computations, which allow to estimate unit volume of heat that may be stored in a tomato-growing greenhouse (concentration: 2.3 plants·m^{-2}) in the period between June and August. Transpiration intensity, energy gain inside facility have been computed using standard dependencies [Kurpaska 2007].

One may observe that estimated maximum heat volume that may be accumulated over a year, exceeds 130 (MJ·m^{-2}) ·year^{-1}.



1 - energy used in plants transpiration process – 558 MJ·m^{-2} = 79.7%
2 - energy exchanged in ventilation process – 10 MJ·m^{-2} = 1.4%
3 - potential heat volume to be stored in the energy accumulator – 132 MJ·m^{-2} = 18.9%

Fig. 2. Potential heat volume that may be accumulated in a greenhouse

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WYKORZYSTANIE NISKOTEMPERATUROWEGO CIEPŁA ZA POMOCĄ POMP GRZEJNYCH W ROLNICTWIE - STAN OBECNY I PERSPEKTYWY

Streszczenie. W pracy w sposób syntetyczny przedstawiono dostępne wyniki badań wykorzystujących pompę ciepła w produkcji rolniczej. Opierając się na średnich wieloletnich obliczono również potencjalne możliwości magazynowania ciepła odpadowego, możliwego do powtórnego wykorzystania w typowej szklarni w której uprawiane są pomidory.

Słowa kluczowe: pompa ciepła, szklarnia, ciepło odpadowe

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