A Long-Term Analysis of the Possibility of Water Recovery for Hydroponic Lettuce Irrigation in Indoor Vertical Farm. Part 1: Water Recovery from Exhaust Air

Anna Pacak 1,*, Anna Jurga 2, Paweł Drąg 3, Demis Pandelidis 1 and Bartosz Kaźmierczak 4

1 Department of Cryogenics and Aerospace Engineering, Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology, 50-370 Wrocław, Poland; demis.pandelidis@pwr.edu.pl
2 Department of Environmental Protection Engineering, Faculty of Environmental Engineering, Wrocław University of Science and Technology, 50-370 Wrocław, Poland; anna.jurga@pwr.edu.pl
3 Department of Control Systems and Mechatronics, Faculty of Control Systems and Mechatronic, Wrocław University of Science and Technology, 50-370 Wrocław, Poland; pawel.drag@pwr.edu.pl
4 Department of Water Supply and Sewerage Systems, Faculty of Environmental Engineering, Wrocław University of Science and Technology, 50-370 Wrocław, Poland; bartosz.kazmierczak@pwr.edu.pl

* Correspondence: anna.pacak@pwr.edu.pl

Featured Application: The presented analysis allows to estimate the sense of using exhaust air as a source of water recovery for the purposes of watering plants in the cultivated halls potentially located in Wrocław (Poland, Lower Silesia).

Abstract: This paper presents the characteristics of the operation of the system for recovery of water from exhaust air in moderate climates in the years 2010–2019. The proposed system for water recovery uses the phenomenon of condensation in a cross-flow heat exchanger operating as an element of the air conditioning system. The parameters of exhaust air behind the heat exchanger have been determined using a mathematical model of the so-called black box. The mathematical model considers the risk of the cross-freezing of the heat exchanger. The calculations carried out for variable parameters of external air during the analyzed period confirm that the system allows to cover the demand for water for lettuce irrigation during the cold and transitional period, which is a major part of the year. It has been noted that the effectiveness of the system is very high (av. 67.12% per year) due to the specific parameters of the internal air in which the lettuce must be grown and the need for continuous air exchange in such facilities. This means that air is a stable source of water recovery, where the recovery rate depends on the parameters of external air.

Keywords: cross-flow heat exchanger; water vapor condensation; threshold air temperature; freeze protection

1. Introduction

The agricultural sector is facing numerous obstacles nowadays. Growing population causes increasing need for food supply, while facing the effects of climate change. The resources available on Earth are increasingly limited, the degradation of agricultural land is progressing, and the pollution of the atmosphere, soil, and water is becoming more visible [1]. Various solutions are implemented worldwide to achieve progressive agricultural sustainability. One of the key examples is food production in vertical farming in ecosystems created in internal spaces (e.g., production hall) [2].
Closed ecosystems allow for maintaining the environment parameters (e.g., air temperature and relative humidity) that are best for plant growth, which would not be possible in conventional outdoor cultivation. The fundamental principles of this method are plant cultivation on several levels (obtained e.g., by using prefabricated modules) and control of indoor environment parameters (temperature, light, relative humidity, and gases). This is essential for yield maximization in a limited space all year round [3]. It also enables farming in places such as a skyscraper, shipping container, or warehouses [2]. Vertical food production might be further increased by using soilless type of cultivation: hydroponics or aeroponics. The common feature of these types of cultivation is the fact that water supplies nutrients to the root zone. In hydroponics, the root zones of plants are located in the water, while in aeroponics the roots are sprayed with mist containing nutrients at appropriate time cycles [4].

The concept of cultivation in closed environment has been studied since the early 1960s, when the first space missions and long-term Antarctic expeditions appeared [5,6]. A review of over 46 plant production facilities in Antarctica has been described in detail in Bamsey et al. (2015) [5]. The second area where closed environment systems have been tested is the space sector. Wheeler (2017) [7] has listed the most important experiments. In both fields, a large proportion of systems used in experiments were hydroponics e.g., BIOS-3 experiment (hydroponic cultivation of grain, vegetables, oil crop (63 m²)) [8], ILSSTF experiment (hydroponic cultivation of grain and vegetable (11.9 m²)) [9], CEEF experiment (hydroponic and solid media cultivation of grains, vegetables, oil crop (150 m²)) [10], Space Ecosystem I experiment (hydroponic cultivation of vegetables (36 m²)) [11], and SMC experiment (hydroponic and solid media cultivation of wheat and vegetables (4.4 m²)) [12].

The experience gained from these experiments, although carried out in relation to space-based applications, has shown that such solutions can also be applied to the terrestrial agriculture industry. In fact, there are many examples of vertical farming facilities all around the world. Recent extensive reviews of working facilities are presented in literature [4,13,14]. Recently a systematic bibliographical review on different approaches and applications of sustainable urban farming (including vertical cultivation) was made by Avgoustaki and Xydis (2020) [15] who analyzed techniques and equipment used, the energy requirements, distribution, and solutions to decrease costs of this sector, and optimization techniques of the cultivation possibilities. It can be seen that water effectiveness is a very important area. Although, the hydroponic system is itself very water efficient, it may be further enhanced by the application water recovery from the air (the condensate). The authors report the possibility of condensation of water from air on a cooling coil panel in an air conditioner [15]. The different approaches are also considered. In fact, water recovery from air might be performed in various ways. It might include use of a typical air-conditioning unit or recuperative exchangers, depending on the location of the cultivation hall. For instance, water is recovered from humidified air in greenhouses in hot climate conditions. Al-Ismaili and Weatherhead [16] developed and validated experimentally a steady-state model of a seawater condenser working in a greenhouse in Oman. The model determines the outlet air parameters such as temperature and humidity, the outlet seawater temperature, and the condensation rate. Perret et al. [17] investigated the water vapor evaporation from the saline in the greenhouse space and water vapor condensation. The condensate is collected for irrigation of plants. The authors gave some recommendations for system design to enhance the condenser performance and to allow recovering more water from the air.

Another topic widely researched by scientists is the condensate recovery from air handling units. The review by Algarni [18] summarizes the current state of knowledge. Eades [19] proposed the water recovery from the air handling unit (AHU) used for the air treatment. The analysis is performed for the laboratory building which needs to be ventilated by 100% of the fresh outdoor air. On the basis of meteorological data and psychometric relationships the amount of condensate was predicted. Licina and Sekhar [20] analyzed the potential of water recovery from the several AHUs operating in hot and humid climates. The captured condensate is reused for precooling the air in another AHU and making up for water losses in the cooling tower. It is found that recovered water allows to perform
the energy savings of approximately 10% and compensate cooling tower water demand over 50%. Ghimire et al. [21] compared nine scenarios of different possibilities of water reuse in commercial buildings in two locations (San Francisco and Washington) using OpenLCA version 1.7.2 software. They considered a rainwater harvesting system and air-condensate harvesting system and the system based on a combination of the two mentioned. Algarni et al. [18] reviewed the progress in research and development of an air-conditioning condensate recovery. In this study the various research directions on condensate production and management of the condensate are presented. The quality and quantity of condensate for different locations and air conditioning systems are summarized.

At certain air parameters, recuperative heat exchangers used in air conditioning systems operate under condensation conditions. Therefore, use of a counter-flow or cross-flow heat exchanger in the air handling unit enables to recover the water condensed from the exhaust air. In case of low external air temperatures, frost or ice may appear in the exchanger. Frosting of recuperation exchangers must therefore be taken into account when carrying out water recovery analyses using this type of equipment.

Deshko et al. [22] analyzed the performance of the cross flow membrane based heat and mass exchanger under the condensation and frost formation conditions. To obtain the desired results the mathematical model was developed and validated on the base of the literature data. Liu et al. [23] established the frosting limits for plate heat and mass exchanger using a mathematical model verified for this purpose. They confirmed that the air flow rate has a significant impact on frosting limits.

The threshold outdoor air temperatures for cross-flow and counter-flow heat exchangers were established by Anisimov et al. [24] and Jedlikowski et al. [25], respectively. The authors created mathematical models that consider various variants of heat and mass transfer that may occur in plate heat exchangers. Using the mathematical models, the operation of the exchangers was analyzed for various parameters of the exhaust and outdoor air.

In greenhouses, it is necessary to dehumidify the air, it was confirmed by a comprehensive review of this field of science [26] (Amani et al.). For these purposes, the authors propose several solutions e.g., natural ventilation systems, sorption systems, heat pumps, etc. The review shows that the recuperative exchanger was tested experimentally for moderate climate conditions as a device for heat recovery, and not for water recovery, and its further uses. It was found that during the cold and transitional period, the exchanger provided the parameters required in the room for most of the experiment. It is mainly related to the parameters of the outdoor air. In the case of indoor vertical farming facility, the possibility of using such a device for ventilation and water recovery was not analyzed previously. In such facilities, it is also necessary to compensate large amounts of transpired water from plants by removing the air from the hall and blowing dry outside air. Implementation of water recovery from an air system will be another advantage of indoor vertical plant cultivation, which are, e.g., increasing the effective arable area for crops by constructing a high-rise building with many levels on the same footprint of land, plant-growing conditions can be optimized to maximize yield by fine-tuning temperature, humidity, and lighting conditions [14]. It will increase the sustainability and the independence of the facility, enabling to work in a closed or partially closed loop.

The aim of this study is to check the potential of water recovery from the exhausted air from the cultivation hall using the cross-flow plate heat exchanger. It needs to be underlined that plate heat exchangers are readily used in air conditioning systems because they have no moving parts, no additional power supply, and their operation is maintenance-free. Basically, the plate heat exchanger working in the air conditioning system allows reducing energy consumption and water may be recovered simultaneously. If the condense is not recovered it is poured out to the sewage system. In this paper it is found whether the amount of water recovered using a cross-flow heat exchanger is sufficient to irrigate the lettuce growing in the ventilated hall. A simplified paper conception is presented in Figure 1.
The performance of the cross-flow heat exchanger, recovering water from the air removed from the indoor vertical farm facility placed in Wrocław (Poland), was analyzed for the years 2012–2019. The diagram of the streams flowing through the exchanger is presented in Figure 2.

The proposed exhaust air water recovery system works as follows. The ambient air is delivered into the hall after airflow treatment in an air handling unit (AHU) cooperating with a cross-flow exchanger (green lines in Figure 2). The cold air is heated (in winter months) in the exchanger, hence the plate of heat exchanger is lowered. When the plate temperature is lower than the dew point of the exhausted airflow (red lines in Figure 2), the condensation of water vapor takes place in the exhausted air channel. The condensate is removed from the exchanger, and transported to a storage tank (2 m$^3$). Before the recovered water is used for watering the cultivation, it is pretreated by e.g., a water purification unit. When ambient air temperature is relatively high and no water is recovered or no water is available in the tank, the plants are supplied with tap water. The switching system is realized by switch over controller. The excess water collected in the tank can be discharged into the sewage system or can be used for other purposes than irrigation of the cultivation: e.g., cleaning purposes, flushing toilets.

2. Materials and Methods

2.1. Weather Data

The following work makes use of the hourly meteorological data (the temperature, the humidity, and the atmospheric pressure) from the Institute of Meteorology and Water Management, National Research Institute stations from the years 2012–2019 (8 years).

The climate of Wrocław is distinguished by features typical of the transitional climate of the mid-latitude zones. The conflicting oceanic and continental influences cause a large variability of the climate, manifesting in an abundance of weather conditions. Due to the location of the city on the outskirts of the Sudetes, this leads to its thermal privilege, being a consequence of the dynamic heating of the air masses settling on the leeward side of the massif. On the other hand, the location of the city within the Oder valley favors weak ventilation and the shaping of unfavorable climatic phenomena which take the form of frequent mists and a higher air humidity [27].
The average yearly temperature in the analyzed period was 10.6 °C, where the lowest average temperatures have of course been recorded in the winter months (on average 3.1 °C in December, 0.5 °C in January, and 1.5 °C in February), and the highest temperatures have been recorded during the summer months (on average 18.8 °C in June, 20.6 °C in July, and 20.3 °C in August). The lowest hourly temperature of –21.3 °C was recorded on 12 February 2012, and the highest one of 37.7 °C was recorded on 8 August 2015. The minimum, the average, and the maximum hourly temperature values, as well as those of the humidity and of the atmospheric pressure, as well as their median and 25% and 75% percentiles, were presented in the form of box plots in Figure 3.

![Figure 3](image_url)

**Figure 3.** The hourly values of the temperature, the humidity, and of the atmospheric pressure in the individual months in Wrocław in the years 2012–2019.

### 2.2. Description of Vertical Indoor Farming Facility and Set-Up Parameters of Growing Plants

To establish the basic assumptions for the water recovery from the exhaust air calculation, it is assumed that the cultivation would be located in a 300 m² hall (20 × 15 m) placed in Wrocław, Poland. The cultivation will be carried out vertically in hydroponic technology using modules similar as produced by the V-farm company [28]. It is assumed that single module has five layers with 43.5 m² of growing area with cultivation density of 19 plants per m². About 12 modules can be placed in the hall considering the farm dimensions, which gives 522 m² of total cultivation area. Each single layer has its own light system assured by LED lamps with photosynthetic photon flux density (PPFD) values of 250 µmol/(m²·s) (164 W/m²). Lettuce is chosen as the base plant for cultivation because leafy greens are among the most popular crops for production in closed indoor farms (Terrafarm, V-farm, Freightfarm, Amyhydro, UrbanGreenFarm, Infarm). Environmental growth conditions (temperature and average water uptake) for lettuce are assessed based on Anderson et al. (2018) [29] and Graamans et al. (2018) [30]. Required temperature for lettuce hydroponic cultivation of indoor air is 23 °C. Average water uptake per square meter is 1.97 L/d
(liters per day, based on [29]), which results in daily water uptake equal 1030 L for whole farm. The relative humidity of exhaust air might be in the range 65–90% [30] hence in this study the exhaust air relative humidity is assumed to be equal to 75%.

2.3. Calculation of the Required Supplied Airflow

The air conditioning system plays an important role in every vertical hydroponic crop. First, it allows to maintain proper and regular air circulation inside the farm, but also provides the \( \text{CO}_2 \) required for plant growth. To analyze the possibility of water recovery the value of treated airflow in air handling unit (AHU) needs to be established. Based on VENTS company materials the required air changes per time unit without any additional \( \text{CO}_2 \) supplementation is 60 air changes per hour [31]. It needs to be underlined that this amount of air changes per time unit is intended for small grow rooms. To estimate the airflow for the entire hall some fundamental calculations were performed using the assumptions available in the literature. To simplify the calculation, it is assumed, that external \( \text{CO}_2 \) addition is possible. The effective plant growth cubature is calculated as multiplication of total cultivation area and height of the lights and plants (about 4.0 m).

Estimation of the air flow assumed that there are constant environmental conditions in the room \( (t_{20} = 23 \, ^\circ\text{C}, \, \text{RH}_{20} = 75\%) \). The maximum heat gains \( (Q_S) \), and maximum humidity gains are assumed to be assimilated by the air conditioning system. In the hall there are latent heat gains related to the water vapor transport to air from plants \( (Q_{L\text{plant}}) \) and sensible heat gains \( (Q_S^{\text{plant}}) \) due to cyclic (16 h per day) illumination of plants with LED lamps with power equal \( P_{\text{LED}} = 164 \, \text{W/m}^2 \). In accordance with the following formula [32], the value of heat gains from LED lamps is calculated as follows:

\[
Q_{\text{LED}}^S = 0.781 \cdot P_{\text{LED}}
\]  

The maximum transpiration stream, and transfer to the internal air is calculated based on a document published by NASA (No. NASA/TP-2015-218570/REV1) [28]. Based on conducted calculations maximum transpiration is equal \( t_r = 1.97 \, \text{L/(m}^2\text{day}) \). The value of latent heat from water-to-air transpiration was calculated using the formula, where \( r \) is heat of vaporization \( (2257 \, \text{kJ/kg}) \), and \( t_r \) is transpiration rate

\[
Q_{L\text{plant}}^L = r \cdot t_r
\]  

The amount of sensible heat assimilated by plants is estimated using formula [31]:

\[
Q_{\text{plant}}^S = \text{LAI} \cdot \rho_a \cdot c_p \cdot \frac{(t_s - t_a)}{r_a}
\]

Sensible heat flux depends on the aerodynamic resistance to heat \( (r_a = 100 \, \text{s/m}) \), the difference between the temperature of the transpiring surface \( (t_s) \) and in the surrounding air \( (t_a) \), \( \text{LAI} = 3 \) which is the leaf area index [33], density of the air \( (\rho_a = 1.20 \, \text{kg/m}^3) \), and the specific heat capacity \( (C_p = 1005 \, \text{J/(kgK)}) \).

The difference between \( t_s \) and \( t_a \) is assumed to be equal to 0.5 \( ^\circ\text{C} \) [34]. The summarized heat gains are presented in Table 1. In this case the sensible heat factor (SHF) equals 0.66, hence the airflow was found by choosing the larger one between the airflow calculated basing on the total cooling loads and moisture gains using following equations:

\[
V_1 = \frac{Q_S^S}{\rho_a \cdot c_p \cdot \Delta t}
\]

\[
V_2 = \frac{\dot{w}}{\rho_a \cdot \Delta x}
\]

\[
V = \max(V_1, V_2)
\]
Table 1. The values of calculated the sensible and latent heat loads.

| Type       | Sensible Heat, kW | Latent Heat, kW |
|------------|-------------------|-----------------|
| Plants     | -9.9              | 29.2            |
| LED lights | 66.8              | -               |

Considering all assumptions, the required supplied airflows are equal to $V_1 = V = 28,500 \text{ m}^3/\text{h}$ and $V_2 = 17,900 \text{ m}^3/\text{h}$ respectively. Where $\Delta t$ is the temperature difference between the supply airflow and exhausted airflow while $\Delta x$ is the humidity ratio difference between supply airflow and exhausted airflow (g/kg). The $c_p$ is the specific heat capacity of moist air (J/(kgK)), $\rho_a$ is a density of the air (kg/m$^3$).

2.4. Cross-Flow Heat and Mass Exchanger

To evaluate the performance of cross-flow exchanger for different conditions the one-dimensional mathematical model is used. The model considers different operation variants. The general variants are “dry”, “wet”, and “frost”. The model includes a possibility for mixed variants to occur, for example “dry” and “wet” occurring simultaneously. Those are described in detail in other publications [24,35]. In this work, the most desirable variant of the exchanger operation is the wet variant, which enables the water recovery from the exhaust air. The operating variants directly depend on the parameters of the exhausted air and outdoor air temperature, hence the mathematical model includes the equations in case of sensible heat transfer in outdoor and exhausted channel (“dry variant”), water vapor condensation in the form of water film in exhausted channel (“wet variant”) and water vapor condensation in the form of ice layer in exhausted channel (“frost variant”).

In this study, the cross-flow exchanger model, based on the $\epsilon$-NTU, method was used, detailed assumptions for the model are presented in [35]. The equations of the mathematical model were implemented into the original compute program in MATLAB environment. The basic equations of the model are shown below.

Overall energy balance within the differential element: in the case of “dry” variant of heat exchange on the surface of the exhaust air passage occurring when plate temperature is higher than the dew point temperature ($t_{DP}$) of the exhausted air ($t_{p2} = t_{p2} > t_{DP}^{2}$):

$$Q_1^S = Q_2^S = \dot{Q}_{\text{cond}}^{\text{plt}}$$  (7)

Overall energy balance within the differential element in the case of “wet” variant of heat and mass exchange on the surface of the exhaust air passage occurs when local plate temperature is lower than the dew point temperature of the exhausted air ($t_{p2} = t_{p2} < t_{DP}^{2}$) and in case of “frost” variant occurring when local plate temperature is lower than 0°C ($t_{p2} = t_{p2} < 0 \degree \text{C}$):

$$Q_1^S = Q_2^S + Q_2^L = \dot{Q}_{\text{cond}}^{\text{plt}}$$  (8)

Using the mathematical model implemented in Matlab, a black box model was developed to determine the operating parameters of the cross-flow unit. The threshold outdoor air temperature was established by performing a calculation loop for different exhausted air parameters and specific heat exchanger number of heat transfer units (NTU = 8).

$$t_{\text{threshold}} = f(\text{NTU}, V_2/V_1, t_{2i}, x_{2i})$$  (9)
Since indoor conditions are constant the threshold air temperature is stable and equal to −2.5 °C. The amount of recovered water was calculated using the equation (where $i$—inlet conditions, $o$—outlet conditions, and $\rho_w$—water density (kg/m$^3$)).

$$w = \frac{V_{\text{air}}(x_{2i} - x_{2o})}{\rho_w}$$

(10)

3. Results and Discussion

The summarized results of the water recovered from the exhaust air are shown in Table 2. The calculations were performed including water storage in a tank with a capacity of 2 m$^3$. The system has a 100% effectiveness in the cold period (months from December to March). During months from June to August the effectiveness of the water recovery system is significantly reduced to average values ranging from 11% to 19%. Months such as May and September are transition months, during which large fluctuations in the effectiveness of the system from minimum values of 24% to maximum values of 75% are observed.

| Month | Performance, % | Performance, m$^3$ |
|-------|----------------|-------------------|
|       | Min Mean Max   | Min Mean Max       |
| I–XII | 61.08 67.12 69.48 | 229.62 252.50 261.91 |
| I     | 100.00 100.00 100.00 | 31.93 31.93 31.93 |
| II    | 100.00 100.00 100.00 | 28.84 29.10 29.87 |
| III   | 100.00 100.00 100.00 | 31.93 31.93 31.93 |
| IV    | 63.58 89.24 100.00 | 19.64 27.58 30.90 |
| V     | 24.18 53.82 75.17 | 7.72 17.18 24.00 |
| VI    | 3.45 19.03 28.26 | 1.07 5.88 8.73 |
| VII   | 4.52 8.24 10.45 | 1.44 2.63 3.34 |
| VIII  | 6.03 11.73 18.63 | 1.93 3.75 5.95 |
| IX    | 31.51 42.55 60.39 | 9.74 13.15 18.66 |
| X     | 68.24 83.55 94.25 | 21.79 26.68 30.09 |
| XI    | 97.56 99.57 100.00 | 30.15 30.77 30.90 |
| XII   | 100.00 100.00 100.00 | 31.93 31.93 31.93 |

In 2012 the maximum effectiveness of system performance was registered. The characteristic parameters describing the operation of the system are shown in the Figure 4. In winter season, a high inflow of water to the reservoir is observed (Figure 4a). The overflow is recorded for 191 days (Figure 4b) till day 110th and from day 284th till the end of the year. It shows a high potential for aerial water recovery in the growing halls. Excess water could be used for other purposes.

In the warm season it is also possible to recover water, but the daily amount of recovered water does not exceed 1 m$^3$ (in the period from day 140th to day 284th of the year see Figure 4a). That is why, during this period of time water is not stored (see Figure 4c) and the system effectiveness varies from 0% to about 48% (Figure 4d).

System operation analysis showed that 2018 is a year in which the lowest system effectiveness equal to 61.08% was recorded. It shows that the exhaust air, which has constant parameters during the year, is a stable source for water recovery. In 2018, the period in which there is no excess water is longer (day 93rd to 297th). The range of 182 days in which the effectiveness of the system is 100% is also lower as confirmed by Figure 5d. For comparison, in 2012 this time lasted for 191 days.
Figure 4. Maximum system effectiveness equal to 69.48% occurred in 2012. (a) Inflow of water to the tank. (b) Overflow of water. (c) Accumulated water in the tank. (d) System performance.

Figure 5. Minimum system effectiveness equal to 61.08% occurred in 2018. (a) Inflow of water to the tank. (b) Overflow of water. (c) Accumulated water in the tank. (d) System performance.

The calculation results of the water recovery system effectiveness for the entire analyzed period are presented in Figure 6. In the cold period, the system has an effectiveness of 100% (blue color). In the warm season, the effectiveness of the systems decreases even to 0%, which is indicated by the red color. It can be concluded that the proposed system is a promising solution in hydroponic growing halls because it allows providing enough water for watering the plants for most of the year. The system also generates excess water, which can be used for other purposes. To create an independent system for recovering water for watering the crop, a supporting system or solution would have to be proposed, the effectiveness of which would be satisfactory during the warm period (e.g., rainwater harvesting [36]).
4. Discussion

On the basis of the results presented in the previous chapter, the proposed water recovery system may be the real alternative to tap water for hydroponic lettuce cultivation located in Wrocław in a cold season. In January, February, March, and December, the system covered 100% of the water demand in the analyzed period of 2012–2019. Moreover, high efficiency was achieved in April (89.2%), October (83.6%), and especially in November (99.6%). It should be emphasized that the obtained results are highly repeatable in years. Due to the very high efficiency of the system in the winter months (daily water recovery greater than demand) and very low system efficiency in the summer months (practically daily water recovery less than the demand), a large volume tank for water collection is not required. In this study a tank with a capacity of only 2 m³ is proposed. The use of a larger reservoir would only slightly increase the efficiency of the system. It would happen only in the spring season (around April), when there was a sudden drop in the efficiency of the system and the accumulated water could replace tap water for a few days. Despite the clear seasonality, the water recovery system from the exhaust air covers an average of 67.1% of the water demand for hydroponic lettuce cultivation located in Wrocław (from 61.1% in 2018 to 69.5% in 2012). This should be considered as a good result. Regarding the cold half-year when there is almost complete coverage of the water demand, this is a very good result.

In order to fully cover the water demand, the proposed system should be equipped with alternative solutions, which are effective in the warm half-year. Due to the characteristics of rainfall in Poland, where statistically 2/3 of the annual rainfall falls in the warm half-year, rainwater harvesting is a promising supplement to the proposed system.

5. Conclusions

This paper presents the operational characteristics of the system for water recovery from exhaust air in moderate climates in the years 2010–2019. The proposed system for water recovery uses the phenomenon of condensation in a cross-flow heat exchanger operating as an element of the air conditioning system. Air conditioning systems maintain the required air parameters in such cultivation halls. The parameters of exhaust air after the heat exchanger were determined using a mathematical model of the so-called black box. The mathematical model considers the risk of frost formation on the plate of heat exchanger. The threshold temperature, for exhaust air parameters \( t = 23 \, \text{°C} \) and \( RH = 75\% \) and the specific number of heat transfer units \( NTU = 8 \) equals \(-2.5 \, \text{°C}\). The calculations carried out for the variable parameters of the outdoor air during the analyzed period, confirm that the system allows to cover the water demand for watering lettuce during the cold and transitional period, which is a major part of the year. It has been noted that the effectiveness of the system is very high (67.1% per year on average) due to the specific parameters of the internal air in which the lettuce must be grown and the need for constant air exchange in such facilities. This means that air is a stable source...
of water recovery, the amount of which depends on the parameters of outdoor air. The effectiveness of the system in the warm period significantly decreases or even disappears, due to a dry heat exchange in the cross-flow exchanger, when there is no condensation of water vapor on the exchanger plates. Therefore, to ensure continuous access to water, the watering system must be equipped with tap water supply or other systems for water recovery. In case of rainfall at a given location, it is necessary to analyze the possibility of rainwater recovery to verify if the aerial water recovery system can efficiently cooperate with the rainwater recovery system. It is possible that in temperate climates these systems may be self-sufficient, which would save a significant amount of water.

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