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The Three-tank Watergy Configuration

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Abstract

The objective of this paper is to propose a generic mathematical model, capable of supporting the design of a custom Watergy plant and future testing of suited control algorithms. The subsystems of the Watergy system are an inside water tank, providing input water for the heat pump, accumu¬lating watering water for plants, and acting like a buffer for the hydraulic operations between tanks, a surface water tank, collecting rain waters, accumulating warm water when the outside tempera¬ture is high and cold water when the outside temperature is low and an underground water tank, accumulating water at constant underground temperature.

Keywords: Watergy, greenhouse three-tank system, heat pump, radiator

1 Introduction. Watergy

Every time we consume electric power produced by conventional methods (hydroelectric, fossil fuel, nuclear) we consume water as well. Still, the association between energy and water is much deeper. Since 2004 a new concept emerged into the Greenhouse industry: the Watergy [1]. *Watergy* is a term coined to describe the interconnection of water and energy [1], [2], [3], etc. The Watergy Greenhouse is a closed greenhouse based on a solar humid-air-collector system, able to efficiently recirculate for a long time an initial amount of water, addressed especially for arid regions. Over the span of two decades, the Watergy concept evolved constantly.

The first configurations [1], [4] consisted of:

1. Heat exchangers for temperature control of the greenhouse.
2. Interconnected water tanks for the storage of heating/cooling energy.
3. A central tower for recycling the plants' irrigation water and recovering water from salt or grey waters, by evaporation and condensation.
4. Control of nutrients and of CO_2.

Today's configurations replaced the condensation tower by liquid desiccant systems, able to extract and store water vapors loaded with energy, during daytime, to recycle the resulted water and to manage the stored energy according to the needs of the plants, at all times [5].

These technologies are perfectly compatible with any other kind of building (residential, industrial, public, etc.), with the Smart Agriculture concept [6], with IoT and AI [7].

A generic Watergy building/greenhouse configuration includes:

1. Heat exchangers for temperature control of the building/greenhouse.
2. Interconnected water tanks for the storage of heating/cooling energy.
3. A desiccant liquid system to collect the excessive humidity from the air, together with its latent heat energy.

The objective of this paper is to propose a generic mathematical model capable of supporting the design of a custom Watergy plant and future testing of suited control algorithms.

2 A Three-Tank Watergy System Configuration

We will use the minimal configuration of a three-tank Watergy system, shown in figure 1.

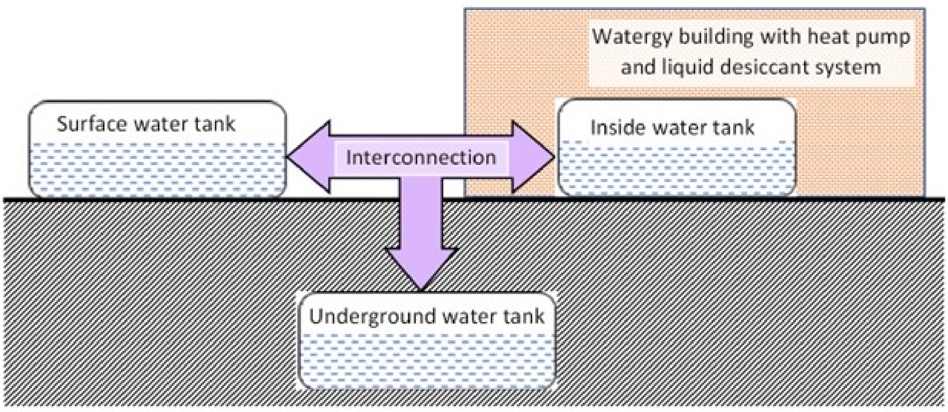


Figure 1: The three-tank Watergy system

The subsystems of the Watergy system are the following:

- IWT the inside water tank provides input water for the heat pump, accumulates watering water for plants and acts like a buffer for the hydraulic operations between tanks. IWT may act as main water pool for aquaponic or hydroponic greenhouses [8].
- SWT the surface water tank collects rain waters, accumulates warm water when the outside temperature is high and cold water when the outside temperature is low.
- UWT the underground water tank accumulates water at constant underground temperature. Natural or artificial aquifers may be used as UWT. If UWT is a proper tank, its thermic connection with the ground should be as tight as possible. If UWT's size is sufficiently large, the heat pump can be connected to it, instead of the usual connection with the phreatic water.

There are at least two reasons for adopting such an architecture:

1. The multi-tank water systems are flexible and facilitate water resources management.
2. Multi-tank water systems are facilitating the water latent energy management (accumulation, storage, use).

The Watergy building/greenhouse is detailed in figure 2.

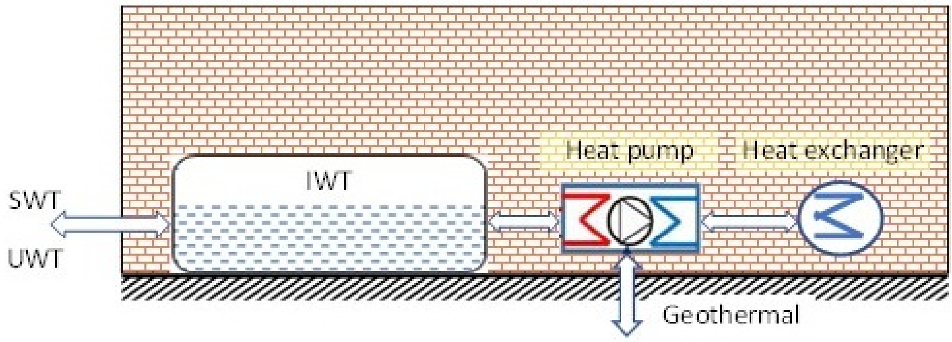


Figure 2: The Watergy building

Indispensable components in modern buildings are the heat pumps (HP), which enable us to take advantage of the ecological heat (solar energy accumulated in soil, water, and air) for economic and ecological heating/cooling. HPs must meet some performance criteria: availability, higher accumulation capacity, higher output temperature, sufficient regeneration, reduced waiting time, etc. The HP's thermal efficiency ε^{PC} is defined as the ratio between the useful thermal energy E_U and the energy consumed to obtain it, E_A:

$$\varepsilon^{PC} = \frac{E_U}{E_A} \tag{1}$$

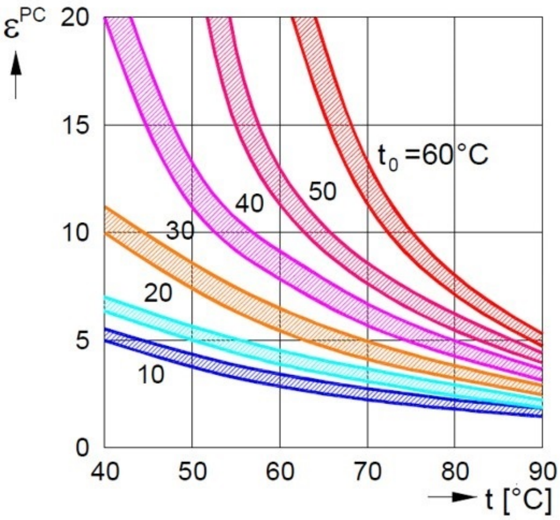
Figure 3 represents the HP's thermal efficiency as function of input (flow) and output (building) temperatures [9] and the radiators' heating curves (Danfoss User Guide ECL Comfort 110) [10] as functions of inside (flow) and outdoor temperatures.

During the heating regime ε^{PC} is the higher the higher the to t_0 is. During the cooling regime ε^{PC} is the higher the lower the t_0 is. That means ε^{PC} is dependent on climate and weather conditions.

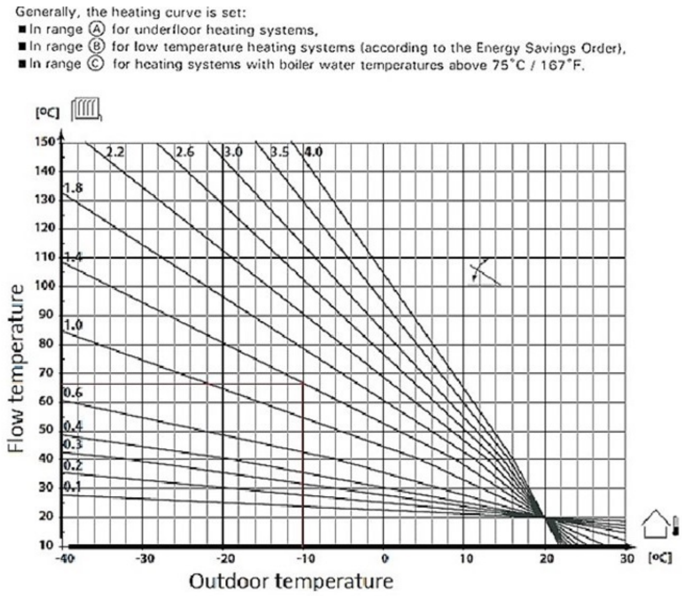
One can improve ε^{PC} simply by increasing t_0 when heating and decreasing it when cooling.

The heat pump's efficiency is also dependent of other factors such as:

1. The heat pump's type (outside air/ground) and quality [11].
2. Constructive conditions such as energetic standards, better for new buildings with heating systems based on surface heat distribution and worse for old un-retrofitted buildings, [11].



(a) Heat pump's efficiency



(b) Radiator heating curves

Figure 3: Heat pumps' efficiency and radiators' heating curves as functions of inside (flow) and outside temperatures

The constructive factors being given, to improve the Watergy buildings' efficiencies we must focus on t and t_0.

According to a thumb rule, heat pumps are recommended to work around a Master Temperature Set-Point $t = 55°C$. At higher temperatures ε^{PC} is decreasing, while reducing t is not a good choice: although ε^{PC} increases, the efficiency of the heat transfer from the radiators or heat exchangers to the interior of the building decreases. This optimization problem has many practical and custom solutions [12], [13], [14] etc.

Our goal is to maximize the Watergy building's efficiency, in any constructive version, by increasing (when heating) or decreasing (when cooling) the temperature of the input water. The three-tank configuration is now revealing its potential: by creating water accumulations of different temperatures, they create the possibility to improve the heat pumps' performance, even to optimize it occasionally.

Basically, in hot weather SWT is hot and UWT is cool while in extremely cold weather SWT is cool – special measures must be taken for avoiding freezing - and UWT is warm. Besides these two operating poles, the Watergy building's system will be configurated by suited commutations between the tanks and the heat pump.

3 Configurating the System

Figure 4 proposes some weather adapted configurations for the three-tank Watergy system.

The first approach consists in the simple classification of the SWT, IWT and UVT temperatures. When heating the building, HP will be fed from the highest temperature tank and will discharge into the other tanks, while when cooling, HP will be fed from the lowest temperature tank.

During hot and frosty weathers the main water source feeding HP is UWT, as in the conventional HP served buildings. IWT plays a buffer role, receiving the discharged HP water and supports the water demands of UWT and SWT. In greenhouses, IWT is watering the plants. Its presence inside the building/greenhouse is increasing thermal inertia.

In non-extreme climates, most of the time the Watergy systems work in mild weather, which implies a more nuanced operation, with SWT more utilized. The idea is to exploit the temperature differences between day and night. The energy accumulated during the day, when the system is in cooling mode, may be used at night, for heating.

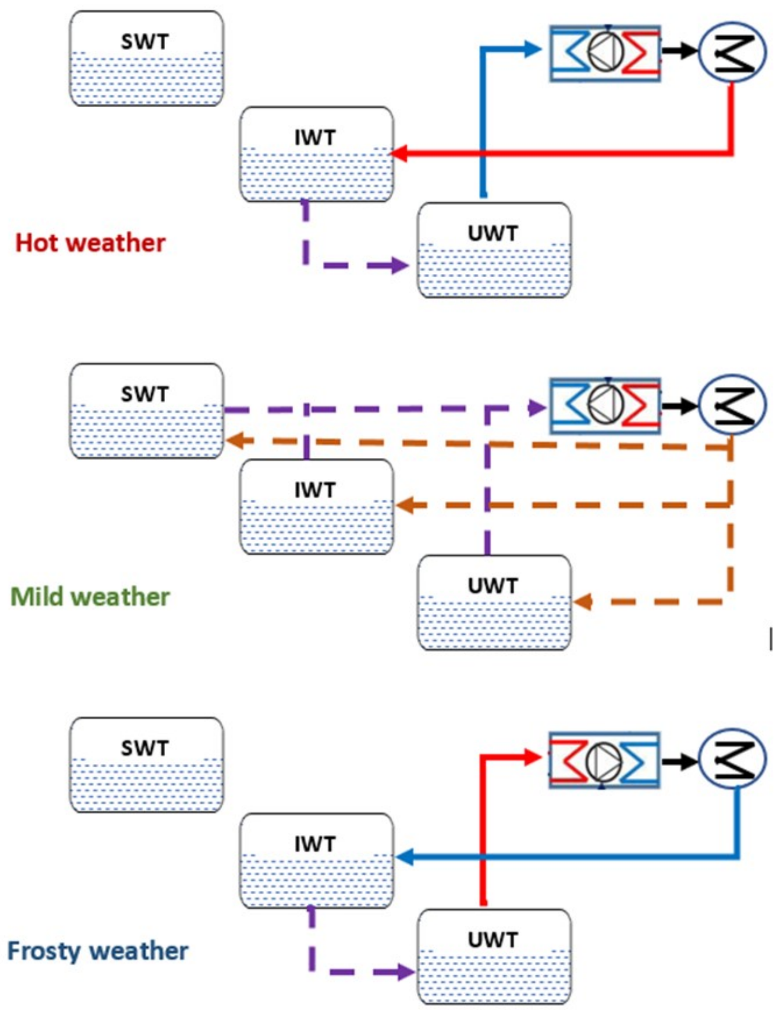


Figure 4: Recommended system configurations, adapted to weather

4 The Mathematical Model

The problem of the three-tank system consists in the simultaneous adjustment of the parameters:

1. The level of the liquid in each tank.
2. The input, transfer, and output liquid flow rates of the system.
3. The water temperatures in each tank.
4. The concentrations of nutrients and other chemicals in each tank.

A structural mathematical model of the three-tank Watergy system is presented in the following. The corresponding system is presented in figure 5.

Ventils V_S, V_I and V_W (watering plants) as well as pumps P_S and P_U adjust the water flows between tanks. The way in which the 3-tanks Watergy system is used doesn't call for the proper equation of the 3-tanks system [15], since connecting all three tanks simultaneously is not desirable.

Considering the height difference H of UWT, we can turn 3-tanks into three 2-tanks connections [16]:

a) The connection between the tanks at the same level SWT and IWT, when the liquid levels h_{SWT} and h_{IWT} depend on the hydrostatic equilibrium, the valves discharge coefficients V_S and V_I and the F_{P_s} flow rate:

$$S_{SWT}\frac{dh_{SWT}}{dt} = F_{P_s} - min(V_S, V_I) \cdot \sqrt{2g(h_{SWT} - h_{IWT})} \quad (2)$$

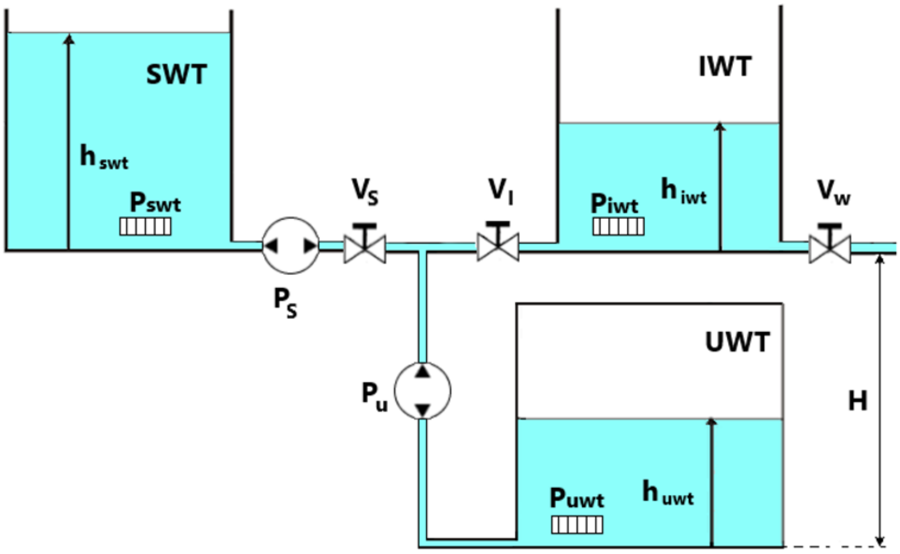


Figure 5: The model's structure

$$S_{IWT}\frac{dh_{IWT}}{dt} = min(V_S, V_I) \cdot \sqrt{2g(h_{SWT} - h_{IWT})} - V_W \cdot \sqrt{2gh_{IWT}} - F_{P_S} \tag{3}$$

One consider pump F_{P_s}'s flow rate sense from IWT to SWT and the discharge coefficient between IWT and SWT as $min(V_S, V_I)$. The discharge coefficient for the plants' watering installation is V_W. S_{SWT} and S_{IWT} are the surfaces of the respective tanks.

b) The connection between SWT and UWT, when the liquid levels h_{SWT} and h_{UWT} depends on the hydrostatic equilibrium with level difference H, the V_S discharge coefficient, and the F_{P_u} flow rate:

$$S_{SWT}\frac{dh_{SWT}}{dt} = F_{P_u} - V_S \cdot \sqrt{2g(H + h_{SWT} - h_{UWT})} \tag{4}$$

$$S_{UWT}\frac{dh_{UWT}}{dt} = V_S \cdot \sqrt{2g(H + h_{SWT} - h_{UWT})} - F_{P_u} \tag{5}$$

c) The connection between IWT and UWT, when the liquid levels h_{IWT} and h_{UWT} depend on the hydrostatic equilibrium with level difference H, the V_I discharge coefficient, and the F_{P_u} flow rate:

$$S_{IWT}\frac{dh_{IWT}}{dt} = F_{P_u} - V_I \cdot \sqrt{2g(H + h_{IWT} - h_{UWT})} - V_W \cdot \sqrt{2gh_{IWT}} \tag{6}$$

$$S_{UWT}\frac{dh_{UWT}}{dt} = V_I \cdot \sqrt{2g(H + h_{IWT} - h_{UWT})} - F_{P_u} \tag{7}$$

The model does not include the contribution of the heat pump recirculating flow, which is simply subtracted from the tank which is feeding HP and added to the tank where HP is evacuating the output water.

The thermal behavior of each tank is driven by its power source ($PSWT, PIWT, PUWT$) which is englobing the convection and radiation energy changes with the environment and the positive (heating) or negative (cooling) contributions of renewable energy sources (mainly sun and geo-thermal). The same equation stands for each water tank (8):

$$V_T(t) \cdot \rho_w \cdot c_w \cdot \frac{d\theta_{out}(t)}{dt} = \{[F_t(t) - F_o(t)] \cdot \rho_w \cdot c_w + \alpha \cdot S\} \cdot [\theta_{in}(t) - \theta_{out}(t)] + P_T(t - \tau) \tag{8}$$

where V_T is the tank's volume $[m^3]$, ρ_w $[kg/m^3]$ water density, c_w $[J/kg \cdot {}^\circ K]$ water specific heat, $\theta[{}^\circ C]$ temperature, $F[m^3/s]$ input and output water flows, $\alpha[W/m^2 \cdot {}^\circ K]$ mean heat transfer coefficients through walls, $S[m^2]$ radiant surfaces, $P[W]$ the heating/cooling power and τ a time delay. θ_{in} is the temperature of the input water flow and θ_{out} is the temperature of the output water flow. Index T refers to SWT, IWT and UWT. The influence of the air inside tanks is neglected.

5 Conclusion

The paper proposes a structural mathematical model for a three tanks Watergy greenhouse system capable of supporting the design custom Watergy buildings and future testing of suited control algorithms. The three water tanks of this Watergy system are located outside and inside the green¬house and underground. This configuration can optimize the performance of the heat pumps which are heating or cooling the building.

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