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The Potential for Digestate Thickening in Biogas Plants and Evaluation of Possible Evaporation Methods

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Rising number of biogas plants (BGP) is associated with a rising amount of digestate, which is a by-product of biogas production. Liquid digestate (LD) is produced in mechanical separation of digestate, and contains valuable nutrients as well as large amounts of water. Treatment of the LD is thus rather expensive for the plant owners. One of the ways to drain the LD and obtain valuable concentrated nutrients is vacuum evaporation. Vacuum evaporation allows to utilize low-potential waste heat which occurs in excessive amounts in BGP. The potential for digestate thickening is further discussed. This paper also compares specific heat consumption and other selected parameters of three types of industrial evaporators, which may be suitable for the LD thickening. Presented results shows that the proposed model of MSF evaporator has the best thermal performance.

1. Digestate thickening potential in BGP

One of the biggest challenges of modern society these days is to decrease impact of human activities on the environment while maintaining potential for sustainable future development and wellbeing of future generations. The European Union has been a world proponent and advocate of environmentally-friendly initiatives and measures. The EU has adopted the so called 20-20-20 Strategy which aims to reduce EU carbon dioxide emissions by 20 % (in comparison to 1990 levels), increase a share of renewable energy sources in the energy mix to 20 %, and increase efficiency of power plants by 20 % (compared to 2007 outlooks) (EC, 2010).

One of the consequences of this EU policy has been an immense increase in number of biogas plants (BGP). There are more than 17 thousand of them in Europe in 2015, total installed capacity exceeds 8.3 GWel (EBA, 2015). The BGP boom was, among others, promoted by significant financial aid that makes BGP an attractive investment opportunity and facilitates an easy expansion of this environmentally-friendly technology. Thanks to power generation from biogas, BGP contribute to reduce consumption of primary sources of energy and decrease CO_2 emissions. In contrast to conventional fossil fuels, BGP preserves natural carbon cycle in nature.

However, BGP also has several disadvantages. One of the most significant ones is an ineffective use of heat that is produced in cogeneration units in biogas combustion. BGP commonly uses only 20–40 % of the heat and the rest is considered waste heat, and is usually not utilized at all. Yet, there are theoretically several ways to utilize the waste heat. The produced heat is mandatorily used for heating of the fermentor (main consumer of the heat). In addition to that, the heat from BGP could be used in a district heating system, greenhouse heating, drying of digestate, sludge and wood sawdust, cooling, and additional power production using ORC and Kalina cycle (Rutz et al., 2012). One of the reasons that none of the possible methods for utilization of the heat is ever explored and executed is the distance of most of the BGPs from industrial zones and populated areas; other reasons include quantity and quality of the heat, which ranges from 80–450 °C; seasonal fluctuations in heat demands (most heat is produced in summer); high costs of certain utilization methods (ORC) and low prices of fossil fuels (Rutz et al., 2012).

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BGP owners further have to face problems related to management of large quantities of digestate. There are no accurate statistics available, but on average, 15 thousand m^3 of digestate per 1 MW_e of installed capacity is quoted to be produced annually (CzBA, 2010). If current BGP capacity in the EU 27, Switzerland, Croatia and Serbia amounts to 8.3 GWel, digestate production in these countries reaches more than 120 million m^3 of digestate. Digestate is a by-product of anaerobic digestion, described in detail in Pontoni et al. (2015), and it preserves minerals from the original materials. Therefore, it may serve as a fertilizer. However, nutrient concentrations in the digestate are rather low. Digestate leaving the fermentor commonly contains only ca. 8 % of dry matter, the rest is water. There are several reasons why the plant owners aim to reduce water from the digestate, and thus reduce its volume and increase its nutrient concentrations.

One of the reasons is transport and storage costs. For small and medium-size BGPs, transport costs may amount up to 40 % of all costs incurred, and their minimization is obviously very much desired (Bojesen et al., 2015). Other motivation may come from legislation; legislators have limited use of agricultural fertilizers in order to protect quality of surface and groundwater (Drosg et al., 2015). Certain areas with intensive animal and plant production generate surplus of digestate; owners are then forced to transport it to distant lands or have it processed in waste water treatment plants.

Basic digestate processing method is separation of digestate into solid and liquid fractions. Processing is done using belt filters and screw press, or decanter centrifuge. Solid fraction in the digestate contain more than 18 % of dry matter (depending on the technology); LD contains 2–4 % of dry matter and takes up most of the original digestate volume. Solid components contain notable amounts of phosphor and ammonia, but in a stable form that is not available to plants. They are therefore mostly used for aeration of soil (Heviánková et al., 2014). Most nutrients remain in the LD; its subsequent treatment may include several steps which aim to obtain concentrated nutrients. Membrane technologies (micro- and ultrafiltration, reverse osmosis), ammonia stripping, and evaporation are commonly employed here. Costs of these particular technologies (in relation to distance of fertilized lands and transport costs) are compared in Drosg et al. (2015). If waste heat is part of the technology, evaporation then seems very promising.

Thickening of LD using evaporation is in many ways similar to thickening of common types of waste water and process water. But evaporation of LD is affected by higher share of dry matter and high viscosity of the suspension. There are many industrial evaporator manufacturers operating on the market, and they offer many product models for different kinds of wastewater. Heat for the evaporation process may be supplied from an external heat source in the form of steam or hot water. A heat pump and mechanical vapour compression are other types of heat source for the process. If there is waste heat available, last two evaporator options mentioned earlier are not that economical. Evaporators commonly have 1 to 3 evaporation chambers; the more evaporation stages are included, the higher is the efficiency of the process. A survey among manufacturers' marketing materials suggests that specific thermal energy consumption of industrial evaporators with external heat source is in the range of 0.1 to 0.87 kWh kg^{-1}, and specific electricity consumption varies between 0.008 and 0.062 kWh per kg of distillate. The particular consumption is strongly dependent on the unit capacity, number of evaporation stages and wastewater thermo-physical properties.

2. Comparison of different evaporation technologies

Design of industrial evaporators using waste heat may differ in various aspects. Their purchase prices and energy demands which affect total payback period differ, too. A list comparing all available evaporators using waste heat is basically impossible to develop, and this paper therefore focuses on comparison of only 3 types of evaporators. These are two commonly available technologies with a basic design: single effect evaporator and multiple effect evaporator, and one less common multi-stage flash evaporator.

In order to compare the technologies, we selected common parameters that reflect normal conditions in BGP (T_{dig}=20 °C, T_{hw}^{in}=90 °C), average liquid digestate properties (cp_{dig}=3.9 kJ kg^{-1} K^{-1}, x_{dig}=0.04 kg kg^{-1}) and limitations of evaporation technologies and their components (TTD_h=10 °C, TTD_c=5 °C, TTD_{ev}=10 °C). Overall coefficient of heat transfer for water/digestate exchanger was determined, using our own experience, as U_h=0.5 kW m^{-2} K^{-1}. Approximation (Eq(1) and (22)) was used for calculation of properties of the evaporator and condenser (El-Dessouky and Ettouney, 2002), and was compensated with a coefficient of F_U=0.6. The coefficient makes up for higher viscosity of the digestate compared to water which also worsens heat and mass transfer in the liquid digestate. The calculation was further limited by maximum attainable external pressure (p_{max}=-0.95 barg) and highest concentration of dry matter in the digestate that still allows for transport of the digestate via regular pumps, that is x_{max}=0.16 kg kg^{-1}. Influence of dry matter on the evaporation was neglected, and we assumed properties of pure water in the calculation. It is assumed that the distillate is pure water only. Specific heat capacity of the water was assumed to be constant (cp_w=4.18 kJ kg^{-1} K^{-1}). Other thermo-physical properties of the water (L_v,T_{sat}) were determined using IAPWS IF-97. Calculations are idealized in the sense that heat and hydraulic pressure drop, and concrete device geometry have not been

considered in the calculations. Negative pressure in chambers was determined using Generalized Reduced Gradient Algorithm in MS Excel 2013 solver. Specific heat consumption (sTh) was an objective function. Liquid digestate flow rate (M_{dig}) is 1 kg/s.
Following equations were used for the comparison; they apply for all types of the evaporators:

$$U_c^w = 1 \cdot 10^{-3} \cdot (1617.5 + 0.1537 \cdot T_{sat} + 0.1825 \cdot T_{sat}^2 - 0.00008026 \cdot T_{sat}^3) \quad (1)$$

$$U_c^{dig} = U_c^w \cdot F_U \quad (2), \qquad sTh = HD/(3600 \cdot M_d) \quad (3)$$

$$LMTD = \frac{(\Delta T_{max} - \Delta T_{min})}{\ln(\Delta T_{max}/\Delta T_{min})} \quad (4), \qquad sA = M_d^{-1} \cdot \sum_{i=1}^{n} A_i \quad (5)$$

2.1 Single effect evaporator

Single effect evaporators have the most simple design but they also have the lowest energy efficiency. Commonly, the evaporation chamber is supplemented with a circuit for waste water heating, and with a condensation section. We have compared the basic evaporator design with forced external hot water heating that uses cooling water for distillate condensation (Figure 1). Performance of single effect evaporator was determined using the following equations:

$$M_{dig} \cdot cp_{dig} \cdot \left(T_{sat}(p_e) - T_{dig}^{in}\right) + M_d \cdot L_v(p_e) = M_{rec} \cdot cp_{dig} \cdot (T_{rec}^{in} - T_{rec}^{out}) \quad (6)$$

$$M_d \cdot L_v(p_e) = M_{cw} \cdot cp_w \cdot (T_{cw}^{out} - T_{cw}^{in}) = A_{cw} \cdot U_{cw}^w \cdot LMTD_{cw} \quad (7)$$

$$M_{rec} \cdot cp_{dig} \cdot \left(T_{rec}^{in} - T_{rec}^{out}\right) = M_{hw} \cdot cp_w \cdot \left(T_{hw}^{in} - T_{hw}^{out}\right) = A_{hw} \cdot U_{hw} \cdot LMTD_{hw} = HD \quad (8)$$

$$T_{rec}^{in} = T_{hw}^{in} - TTD_h \quad (9), \qquad T_{hw}^{out} = T_{rec}^{out} + TTD_h \quad (10)$$

$$T_{cw}^{out} = T_{sat}(p_e) - TTD_c \quad (11), \qquad M_{dig} \cdot x_{dig} = M_{conc} \cdot x_{conc} \quad (12)$$

$$M_{dig} = M_{conc} + M_d \quad (13), \qquad sM_{cw} = M_{cw}/M_d \quad (14)$$

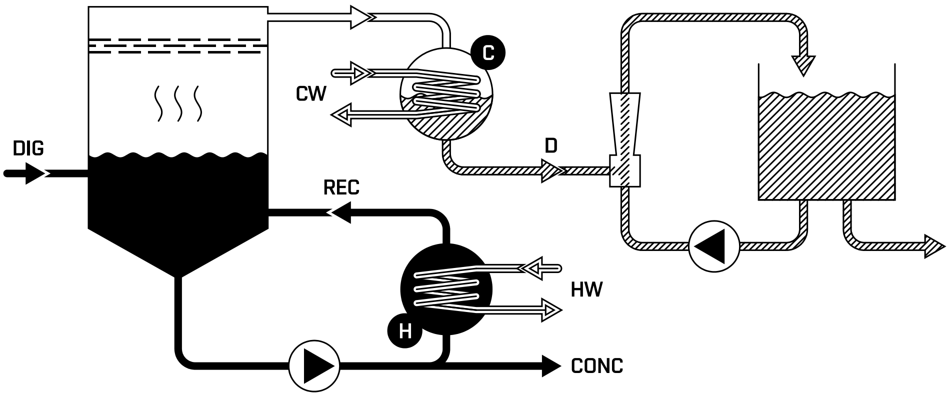

Figure 1: Design of single effect evaporator, used in the calculations

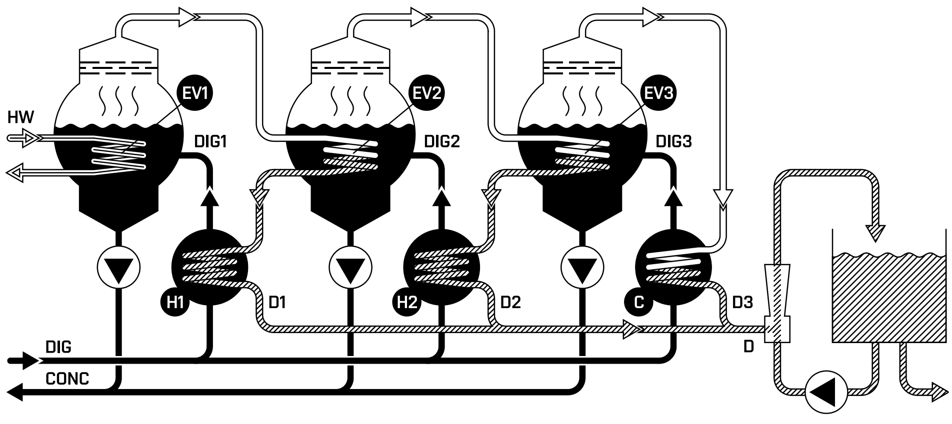

Figure 2: Design of multiple effect evaporator, used in calculations

2.2 Multiple effect evaporator

Multiple effect evaporators (MEE) have overcome major operational deficiencies in latter half of 20th century thanks to boom of desalination industry (El-Dessouky and Ettouney, 2002). In addition to desalination, they are frequently used in food industry, paper industry and petrochemical industry. Prado et al. (2015) have researched application of MEE in ethanol production. For purposes of this paper, we opted for a 3-stage parallel flow arrangement with a horizontal falling film evaporator and hot water heating (Figure 2). The LD is preheated using the condensing distillate from the previous chamber prior to entering the chamber. Certain manufacturers do offer this design. This design type has, compared to other MEE evaporators, a more simple construction that may be suitable for thickening of the LD. LD flow rate and evaporator heat transfer surface are assumed to be similar in every chamber. Performance of this type of MEE was determined using the following equations:

This applies only to evaporation chamber no 1:

$$M_{dig,1} \cdot cp_{dig} \cdot \left(T_{sat}(p_{e,1}) - T_{dig,1}\right) + M_{d,1} \cdot L_v\left(p_{e,1}\right) = M_{hw} \cdot cp_w \cdot (T_{hw}^{in} - T_{hw}^{out}) \quad (15)$$

$$M_{hw} \cdot cp_w \cdot \left(T_{hw}^{in} - T_{hw}^{out}\right) = A_{ev,1} \cdot U_{ev,1}^{dig} \cdot LMTD_{ev,1} = HD \quad (16)$$

$$T_{hw}^{out} = T_{sat}(p_{e,1}) + TTD_h \quad (17)$$

This applies only to evaporation chamber no 3:

$$M_{dig,3} \cdot cp_{dig} \cdot \left(T_{dig,3} - T_{dig}\right) = M_{d,3} \cdot Lv\left(p_{e,3}\right) = A_{c,3} \cdot U_{c,3}^{dig} \cdot LMTD_{c,3} \quad (18)$$

For evaporation chamber i, the following generally applies:

$$M_{dig,i} \cdot cp_{dig} \cdot \left(T_{dig,i} - T_{dig}\right) = M_{d,i} \cdot cp_w \cdot (T_{sat}\left(p_{e,i}\right) - T_{d,i}) \quad (19)$$

$$M_{dig,i} \cdot cp_{dig} \cdot \left(T_{sat}\left(p_{e,i}\right) - T_{dig,i}\right) + M_{d,i} \cdot L_v\left(p_{e,i}\right) = M_{d,i-1} \cdot Lv\left(p_{e,i-1}\right) \quad (20)$$

$$M_{dig,i} \cdot cp_{dig} \cdot \left(T_{dig,i} - T_{dig}\right) = A_{h,i} \cdot U_{h,i} \cdot LMTD_{h,i} \quad (21)$$

$$U_{ev,i}^{w} = 1 \cdot 10^{-3} \cdot (1939.4 + 1.40562 \cdot T_{sat}\left(p_{e,i}\right) - 0.020752 \cdot (T_{sat}\left(p_{e,i}\right))^2 - 0.0023186 \cdot (T_{sat}\left(p_{e,i}\right))^3) \quad (22)$$

$$U_{ev}^{dig} = U_{ev,i}^{w} \cdot F_U \quad (23), \qquad M_{d,i-1} \cdot Lv\left(p_{e,i-1}\right) = A_{ev,i} \cdot U_{ev,i}^{dig} \cdot LMTD_{ev,i} \quad (24)$$

$$M_{dig} \cdot x_{dig} = M_{conc,i} \cdot x_{conc,i} \quad (25), \qquad M_{dig,i} = M_{conc,i} + M_{d,i} = M_{dig}/3 \quad (26)$$

And finally:

$$M_d = \sum_{i=1}^{3} M_d^i \quad (27), \qquad sM_{cw} = M_{dig}/M_d \quad (28)$$

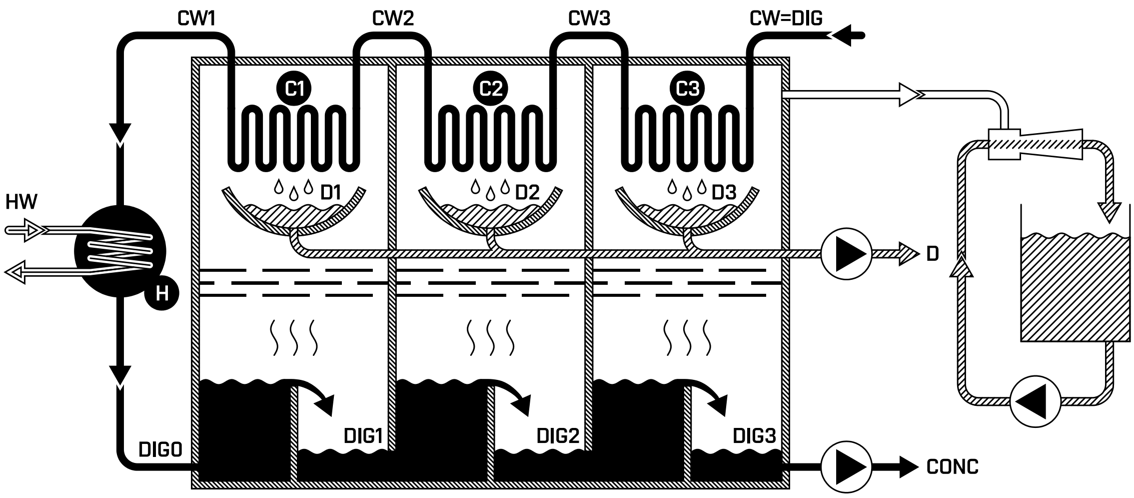

Figure 3 Design of multiple effect evaporator, used in calculations

2.3 Multistage flash evaporator

Multistage flash evaporators (MSF) are commonly employed in desalination industry. Although the technology has been around for a while, its role in large-scale desalination is irreplaceable, and MSF is still a subject of

many R&D (Sowgath and Mujtaba, 2015). Manufacturers basically don't offer the technology for thickening of waste water and process water. However, MSF evaporators have a distinct advantage over MEE in the sense that evaporation does not occur on heat transfer surface but directly in the liquid bath thanks to decreased pressure. 3-stage "once through" type (Figure 3), with a simple construction, was selected for the comparison. Hot water is the heat source. Similar heat transfer surface area is assumed for all condenser calculations. This allows to decrease manufacturing costs of the unit. Performance of this type of MSF was determined using the following equations:
This applies only to evaporation chamber no 1 and heater:

$$M_{hw} \cdot cp_w \cdot (T_{hw}^{in} - T_{hw}^{out}) = M_{dig} \cdot cp_{dig} \cdot (T_{dig,0} - T_{cw,1}) = A_h \cdot U_h \cdot LMTD_h = HD \quad (29)$$

$$T_{dig,0} = T_{hw}^{in} - TTD_h \quad (30), \qquad M_{dig,0} = M_{dig} \quad (31)$$

For evaporation chamber i, the following generally applies:

$$M_{dig,i-1} \cdot cp_{dig} \cdot \left(T_{dig,i-1} - T_{sat}(p_{e,i})\right) = M_{d,i} \cdot L_v(p_{e,i}) \quad (32)$$

$$M_{dig} \cdot cp_{dig} \cdot (T_{cw,i+1} - T_{cw,i}) = A_{c,i} \cdot U_{c,i} \cdot LMTD_{c,i} = M_{d,i} \cdot L_v(p_{e,i}) \quad (33)$$

$$T_{cw,i} = T_{sat}(p_{e,i}) - TTD_c \quad (34), \qquad T_{dig,i} = T_{sat}(p_{e,i}) \quad (35)$$

$$M_{dig,i} = M_{dig,i-1} - M_{d,i} \quad (36), \qquad M_{dig} \cdot x_{dig} = M_{conc} \cdot x_{conc} \quad (37)$$

This applies only to evaporation chamber no 3:

$$M_{dig} \cdot cp_{dig} \cdot (T_{cw,3} - T_{dig}) = M_{d,3} \cdot Lv(p_{e,3}) \quad (38), \qquad M_{conc} = M_{dig,3} \quad (39)$$

And finally we can use Eq. (27) and (28) to determine M_d and sM_{cw}.

3. Results and discussion

Table 1 presents the results. As expected, SEE with specific heat consumption of 0.69 kWh/kg seems to be the least effective type of evaporator. However, MEE also has rather low efficiency with sTh equal to 0.62 kWh/kg. For this reason, parallel/cross flow configuration could be considered for further research. On the other hand, MSF unit has the lowest sTh of 0.33 kWh/kg. Obtained results are comparable with performance of industrial evaporators for other kinds of waste water. Although the heat consumption of selected evaporators is rather high, it is not surprising. The reasons lie in thermal-hydraulic properties of LD which affected low U values. SEE unit has the highest requirements on heat transfer area (982.9 $m^2kg^{-1}s^{-}1$), which greatly increases manufacturing costs. MEE unit has low sA values; compared to MSF, it has higher temperature differences on heat transfer area (up to 38 °C). Other disadvantages of SEE include high requirements on external cooling water sM_{cw}, consumption is distinctly higher than for the other two technologies (cooling is secured by preheating of the LD). On the other hand, advantages include utilization of most of the temperature gradient (cooling up to 43 °C) and theoretical ability to preserve high amounts of dry matter in the concentrate (even if there is little dry matter entering the unit). Levels of liquid digestate thickening in MEE and MSF are rather low. If x_{max}=0.16 kg kg^{-1} should be achieved, partial recirculation of the concentrate would have to be introduced. MEE technology has the lowest requirements on vacuum quality, negative pressure of -0.88 barg is enough for optimum performance.

Table 1: Results of comparison of three types of evaporators for liquid digestate thickening

	$sTh(kWh/kg)$	$sA(m^2/kg/s)$	$sM_{cw}(kg/kg)$	$x_{conc}(kg/kg)$	$p_{max}(barg)$
SEE	0.69	982.9	73.6	0.16	-0.95
MEE	0.62	141.9	15.5	0.043	-0.88
MSF	0.33	426.4	14.5	0.043	-0.94

4. Conclusion

As the number of BGP rises, there is an eminent need for a technology, which can effectively thicken LD from anaerobic digestion. According to presented assumptions, more than 120 million m^3 of digestate is produced yearly in Europe. Thanks to the permanent excess of waste heat from cogeneration of biogas, vacuum evaporation seems to be the promising technology. Our ambition was to compare specific heat consumption and other relevant parameters of three types of industrial evaporators that we have deemed sufficient for thickening of LD in biogas plants. Evaporators were selected for their simple construction which might make the liquid digestate processing easy. Our calculations prove that MSF is most efficient in use of the heat (0.33 kWh/kg of the distillate); MSF is followed by MEE (0.62 kWh/kg) and SEE (0.69 kWh/kg). Performance of selected evaporators are comparable with different types of industrial evaporators although they are affected by worse thermal-hydraulic properties of the LD. MEE unit has the lowest requirements on heat transfer area (141.9 $m^2kg^{-1}s^{-1}$). LD thickening to 16 % dry matter concentrations, without any further technology adjustments, may be achieved only with SEE technology.

Nomenclature:

A	Heat surface area, m^2
cp	Specific heat capacity, kJ kg^{-1} K^{-1}
HD	Heat duty of heating water, kW
F_U	correction coefficient for liquid digestate, -
$LMTD$	Logarithmic mean temperature difference, °C
L_v	Heat of vaporization, kJ kg^{-1}
M	Mass flow rate, kg s^{-1}
Mh	Mass flow rate, kg h^{-1}
n	Number of heat exchangers in the system
p	Pressure in an evaporation chamber, barg
sA	Specific heat surface area, m^2 kg^{-1}
sEl	Specific electricity consumption, kWh kg^{-1}
sEn	Specific overall energy consumption, kWh kg^{-1}
sM	Specific water consumption, kg kg^{-1}
St	Number of evaporation effects (stages)
sTh	Specific thermal energy consumption, kWh kg^{-1}
T	Temperature, °C
TTD	Terminal temperature difference, °C
U	Overall heat transfer coeff., kW m^{-2} K^{-1}
x	Dry matter content, kg kg^{-1}

Indices

h	Water/Liquid digestate heat exchanger
hw	Heating water
c	Condenser
$conc$	Concentrate
cw	Cooling water
d	Distillate
dig	Liquid digestate
e	Equilibrium
ev	Evaporator
i	Effect number
rec	Recirculation
sat	Saturation
w	Water

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