GEOFOOD – Validation of an energy model for recirculating aquaculture systems

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Referaat
Dit rapport bevat een beschrijving en validatie van het energie model voor recirculerende aquacultuur systemen (RAS), dat is ontwikkeld binnen het EU-project GEOFOOD. Het model is gevalideerd op basis van data die is verzameld uit het viskweek systeem dat is gerealiseerd in onderzoeksfaciliteiten van Wageningen University & Research in Bleiswijk, Nederland. Projectpartner Landing Aquaculture ontworpen en bouwden het systeem in 2019. Het gevalideerde model kan worden ingezet om de energievraag van RAS te simuleren voor verschillende klimaten, systeemontwerpen en vissoorten. Ook evaluatie van het gebruik van geothermische (rest)warmte voor de verwarming van RAS valt onder de toepassingen van het model.

Abstract
This report contains a description and validation of the energy model for recirculating aquaculture systems (RAS), which was developed within the EU project GEOFOOD. The model has been validated using data that was collected from the fish farming system at the research facilities of Wageningen University & Research in Bleiswijk, the Netherlands. Project partner Landing Aquaculture designed and built the system in 2019. The validated model can be used to simulate the energy demand of RAS for different climates, system designs and fish species. Evaluation of the use of geothermal (residual) energy for heating RAS also falls under the model's applications.

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1 Introduction

GEOFOOD is a GEOTHERMICA research, innovation and demonstration project that aims to determine how and to what extent the heat use efficiency of geothermal wells can be increased by means of circular food production systems. In these systems several activities such as agricultural production, (waste)water treatment, nutrient recovery, as well as food processing are connected by the exchange of energy and mass flows. Since the subsystems have a variety of heating (and cooling) requirements throughout the year, they could be operated as a thermal treatment network in order to optimise the heat extraction from a geothermal well.

To investigate the potential of this principle one of the main research topics within the GEOFOOD project is the direct use of geothermal energy for aquaponics. Aquaponics is a farming system that connects hydroponic cultivation of crops with aquaculture by exchanging water- and nutrient flows. Building on this circular concept, a predictive model was developed to design and assess geothermal aquaponic systems consisting of a geothermal well, a greenhouse and a recirculating aquaculture system (RAS).

Figure 1 shows a schematic overview of the model. A starting point of the model is a geothermally heated greenhouse which utilizes a RAS as a sink for residual heat. This means that the greenhouse heat demand has priority over RAS heat demand. The RAS is therefore supplied with heat in two distinct ways. First, whenever the greenhouse does not require the full heating capacity of the geothermal well, the remaining capacity can be utilized directly by the RAS. Second, the greenhouse can supply residual heat to the RAS when the temperature of the return water from the pipe heating system in the greenhouse exceeds the temperature of the fish rearing water (i.e. cascading).

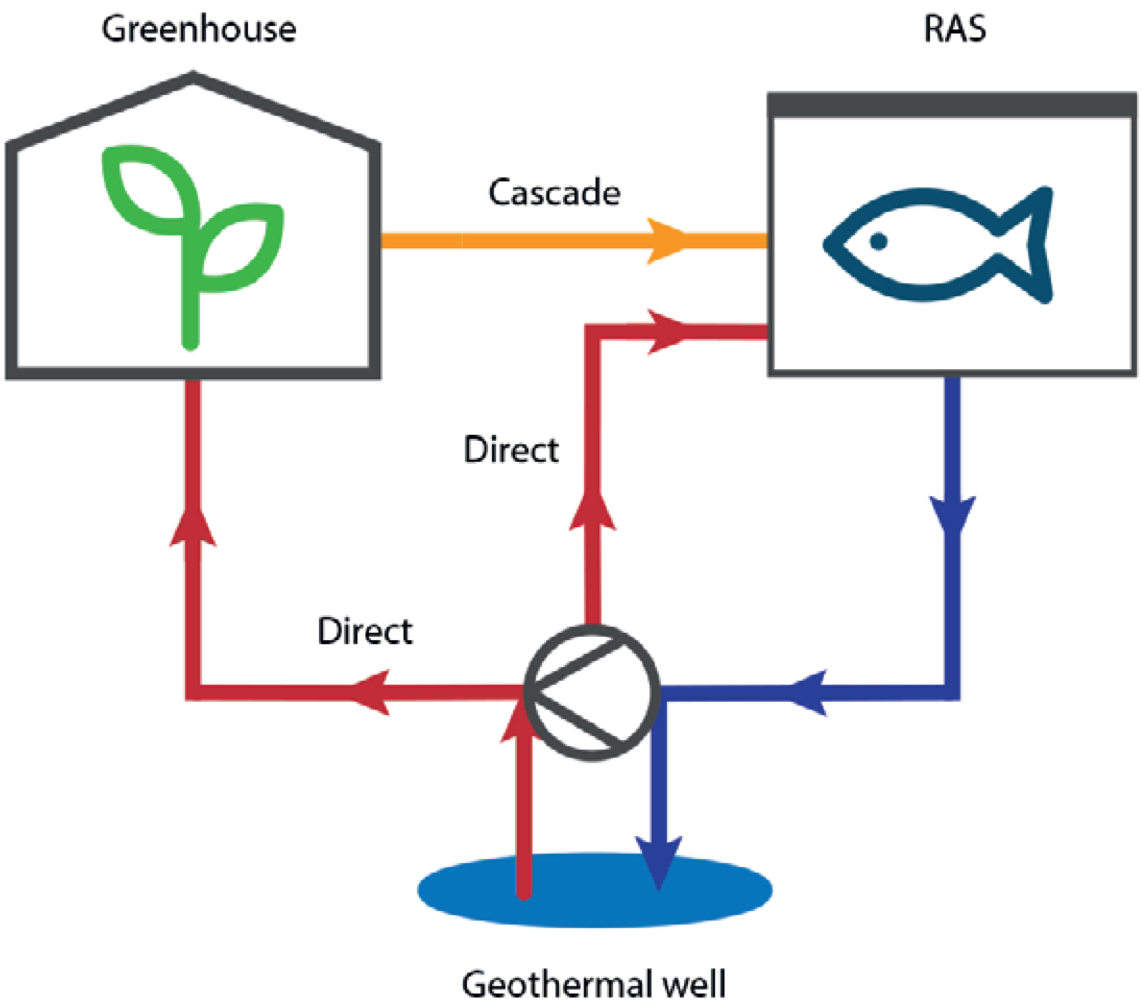

Figure 1 *Schematic overview of the modelled geothermal aquaponic system.*

The core model consists of two parts to calculate hourly values for the energy and mass flows: (1) a greenhouse climate and energy model and (2) an energy model for recirculating aquaculture systems (RAS) that was newly developed within the GEOFOOD project. The combined outputs as well as geothermal well parameters are used to compute when and how much heat is extracted by an geothermal aquaponics. A full description of the overall model can be found in Boedijn et al. 2019a.
In a report by Boedijn et al. 2019b, the functionality and applicability of the geothermal aquaponic model are demonstrated through scenarios for tomato- and lettuce greenhouse production, combined with a RAS facility that produces pike-perch.

To validate the RAS energy model, data was collected from research facilities at Wageningen University & Research, located in Bleiswijk, the Netherlands. Construction of the experimental RAS and aquaponic system took place from January until May 2019. After completion the facilities were used, among other functions, to gather data by running fish- and lettuce production trials until June 2020. For a full description of the RAS facilities please refer to the design report by Landing Aquaculture, 2019. For more information on the aquaponic design and heating installation please refer to the progress reports (Boedijn et al. 2020; Boedijn, Poot, et al. 2019a, 2019b).

This report contains a validation of the RAS energy model based on the collected data from the research facilities at Wageningen University & Research, located in Bleiswijk, the Netherlands. Chapter 2 contains a (brief) description of the RAS energy model, distinguishing the key heat fluxes used for the overall energy balance of the fish rearing system. Chapter 3 gives an overview of the materials (i.e. research facilities and sensors) and methods that were available and selected to gather data and perform a validation study. Chapter 4 shows the results and Chapter 5 contains the discussion and conclusions.

2 Model description

The RAS energy model has been newly developed for the GEOFOOD project in order to predict the heat demand of RAS facilities. Project partner Landing Aquaculture provided Wageningen University & Research with input on energy and mass balances applied to indoor recirculating aquaculture. Some adaptations and improvements resulted in a model that was implemented in MATLAB to enable year-round simulations. The RAS energy model describes the heat balance as presented in equation 1.

$$Q_{demand} = Q_{building\ loss} + Q_{water\ exchange} + Q_{evaporation} + Q_{ventilation} - Q_{fish} - Q_{equipment} \qquad (1)$$

Q_{demand}	: overall heat demand of the RAS facility	[W/m^2]
$Q_{building\ loss}$	: heat loss from the building	[W/m^2]
$Q_{water\ exchange}$	: heat demand due to water exchange	[W/m^2]
$Q_{evaporation}$	: heat loss due to evaporation	[W/m^2]
$Q_{ventilation}$	: heat loss due to ventilation	[W/m^2]
Q_{fish}	: heat produced by the fish	[W/m^2]
$Q_{equipment}$	: heat produced by the equipment	[W/m^2]

To calculate all heat flows several inputs are required that represent the outdoor climate, design and management of the RAS facility as well as the species of fish cultivated. An overview of the inputs is presented in Table 1.

Table 1
Nomenclature of input variables RAS model.

Variable	Description	Unit
A_{cover}	area of cover	[m^2]
A_{floor}	area of RAS facility	[m^2]
A_{water}	area of water surface	[m^2]
P	power of equipment units	[W]
R_{FO}	feed to oxygen ratio	[kg/kg]
R_{OH}	oxygen to heat ratio	[J/kg]
RH_{in}	target relative humidity of indoor air	[%]
RH_{out}	relative humidity of outdoor air	[%]
T_{in}	target indoor air temperature	[ºC]
T_{out}	outdoor air temperature	[ºC]
T_{source}	source water temperature	[ºC]
T_{tank}	target tank water temperature	[ºC]
U_{cover}	heat loss coefficient cover	[W/m^2 K]
W_{feed}	feeding rate	[kg/s]
$W_{infiltration}$	air infiltration rate	[m^3/s]
W_{water}	water exchange rate	[m^3/s]
η	efficiency of equipment units	[-]

Heat loss from the building consists of losses through the walls, roof, floor and due to infiltration. These are calculated using equations 2.A to 2.C respectively. Equation 2.B is based on heat loss through the floor along the building perimeter as described by Timmons et al. 2018. It is assumed that the building is an insulated, opaque structure where heat gain due to solar radiation does not play a significant role.

$$Q_{cover} = U_{cover} \left(\frac{A_{cover}}{A_{floor}} \right) (T_{in} - T_{out}) \qquad (2.A)$$

Q_{cover}	: heat loss through walls and roof	[W/m^2]
U_{cover}	: cover heat loss coefficient	[W/m^2 K]
A_{cover}	: cover area	[m^2]
A_{floor}	: RAS facility area	[m^2]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

$$Q_{floor} = U_{perimeter} \frac{A_{cover}}{A_{floor}} (T_{in} - T_{out}) \qquad (2.B)$$

Q_{floor}	: heat loss through floor	[W/m^2]
$U_{perimeter}$	: empirical constant for floor heat loss	[W/m K]
L	: building perimeter	[m]
A_{floor}	: RAS facility area	[m^2]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

$$Q_{infiltration} = U_{infiltration} \frac{\rho_{air}\, cp_{air}}{A_{floor}} (T_{in} - T_{out}) \qquad (2.C)$$

$Q_{infiltration}$	: heat loss due to infiltration	[W/m^2]
$W_{infiltration}$	: infiltration rate	[m^3/s]
ρ_{air}	: density of air	[kg/m^3]
cp_{air}	: specific heat of air	[J/kg K]
A_{floor}	: RAS facility area	[m^2]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

RAS facilities have an exchange of water with the environment that depends on requirements of the cultivated fish species, growing density and installed filter equipment. Some water leaves the system by means of evaporation and splashing. However, the main outflow consists of water that can no longer be recirculated due to quality constraints (such as nitrate concentration). The outgoing water has to be replenished with water from a suitable source (e.g. treated rainwater or ground water). The energy demand to heat up the inflow of source water to tank water temperature is calculated according to equation 3.

$$Q_{water\ exchange} = W_{water} \frac{\rho_{water}\, cp_{water}}{A_{floor}} (T_{tank} - T_{source}) \qquad (3)$$

$Q_{water\ exchange}$	: heat demand due to water exchange	[W/m^2]
W_{water}	: water exchange rate	[m^3/s]
ρ_{water}	: density of water	[kg/m^3]
cp_{water}	: specific heat of water	[J/kg K]
A_{floor}	: RAS facility area	[m^2]
T_{tank}	: tank water temperature	[°C]
T_{source}	: source water temperature	[°C]

The rate of evaporation from the fish tanks and filter tanks depends on the amount of open water surface and the indoor climate (i.e. temperature and humidity of air). The heat loss associated with evaporation is calculated with equation 4. This empirical equation from ASHRAE, 2004 has been applied within aquaculture to a shrimp RAS facility by Li et al. 2008.

$$Q_{evaporation} = \frac{A_{water}}{A_{floor}} (0.089 + 0.0782\ v)\ (P_{water} - P_{air}) \qquad (4)$$

$Q_{evaporation}$	: heat loss due to evaporation	[W/m^2]
A_{water}	: water surface area	[m^2]
A_{floor}	: RAS facility area	[m^2]
v	: air velocity over water surface	[m/s]
P_{water}	: saturation vapour pressure evaluated at tank water temperature	[Pa]
P_{air}	: saturation pressure evaluated at dew point temperature of indoor air	[Pa]

The units for the constants 0.089 and 0.0782 are in W/(m^2 Pa) and W s/(m^3 Pa) respectively.

To avoid the accumulation of moisture and carbon dioxide within the facility, the indoor air must be exchanged with outside air by ventilation. Within the model it is assumed that the ventilation rate is driven by the rate of evaporation. The ventilation rate and resulting heat demand are calculated with equations 5.A and 5.B respectively.

$$W_{ventilation} = \frac{W_{evaporation}}{\rho_{air}\ (x_{in} - x_{out})} \qquad (5.A)$$

$W_{ventilation}$	: ventilation rate	[m^3/s]
$W_{evaporation}$	: evaporation rate	[kg/s]
ρ_{air}	: density of air	[kg/m^3]
x_{in}	: indoor humidity ratio	[kg/kg]
x_{out}	: outdoor humidity ratio	[kg/kg]

$$Q_{ventilation} = W_{ventilation} \frac{\rho_{air}\ cp_{air}}{A_{floor}} (T_{in} - T_{out}) \qquad (5.B)$$

$Q_{ventilation}$	: heat loss due to ventilation	[W/m^2]
$W_{ventilation}$	: ventilation rate	[m^3/s]
ρ_{air}	: density of air	[kg/m^3]
cp_{air}	: specific heat of air	[J/kg K]
A_{floor}	: RAS facility area	[m^2]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

The heat produced by fish is based on the feeding rate and metabolism of the fish. It is calculated using equation 6. Another input of energy is the significant amount of electrical equipment that RAS facilities contain to recirculate and treat water (e.g. pumps, drum filters, fans, UV systems and ozone generators). The heat produced by this equipment is calculated using equation 7.

$$Q_{fish} = W_{feed} \frac{R_{FO} R_{OH}}{A_{floor}} \qquad (6)$$

Q_{fish}	: heat produced by fish	[W/m^2]
W_{feed}	: feeding rate	[kg/s]
R_{FO}	: feed to oxygen ratio	[kg/kg]
R_{OH}	: oxygen to heat ratio	[J/kg]
A_{floor}	: RAS facility area	[m^2]

$$Q_{equipment} = n\, P \frac{1 - \eta}{A_{floor}} \qquad (7)$$

$Q_{equipment}$	: heat produced by equipment	[W/m^2]
n	: number of equipment units	[-]
P	: power of equipment	[W]
η	: efficiency	[-]
A_{floor}	: RAS facility area	[m^2]

3 Experiment setup

3.1 RAS research facilities

The data required for model validation was gathered from the research facilities at Wageningen University & Research, located in Bleiswijk, the Netherlands. Between January and May 2019 a recirculating aquaculture system (RAS) was constructed by project partner Landing Aquaculture within an existing greenhouse compartment of 144 m^2. Figure 2 shows an overview of the RAS which was part of a larger decoupled aquaponic system. The RAS has a total water volume of about 55 m^3 of which 36 m^3 are fish tanks. Total water surface is 34 m^2 (i.e. fish tanks and part of the biofilter). System flow reaches 60-80 m^3/h and retention time in the fish tanks is 30-60 minutes.

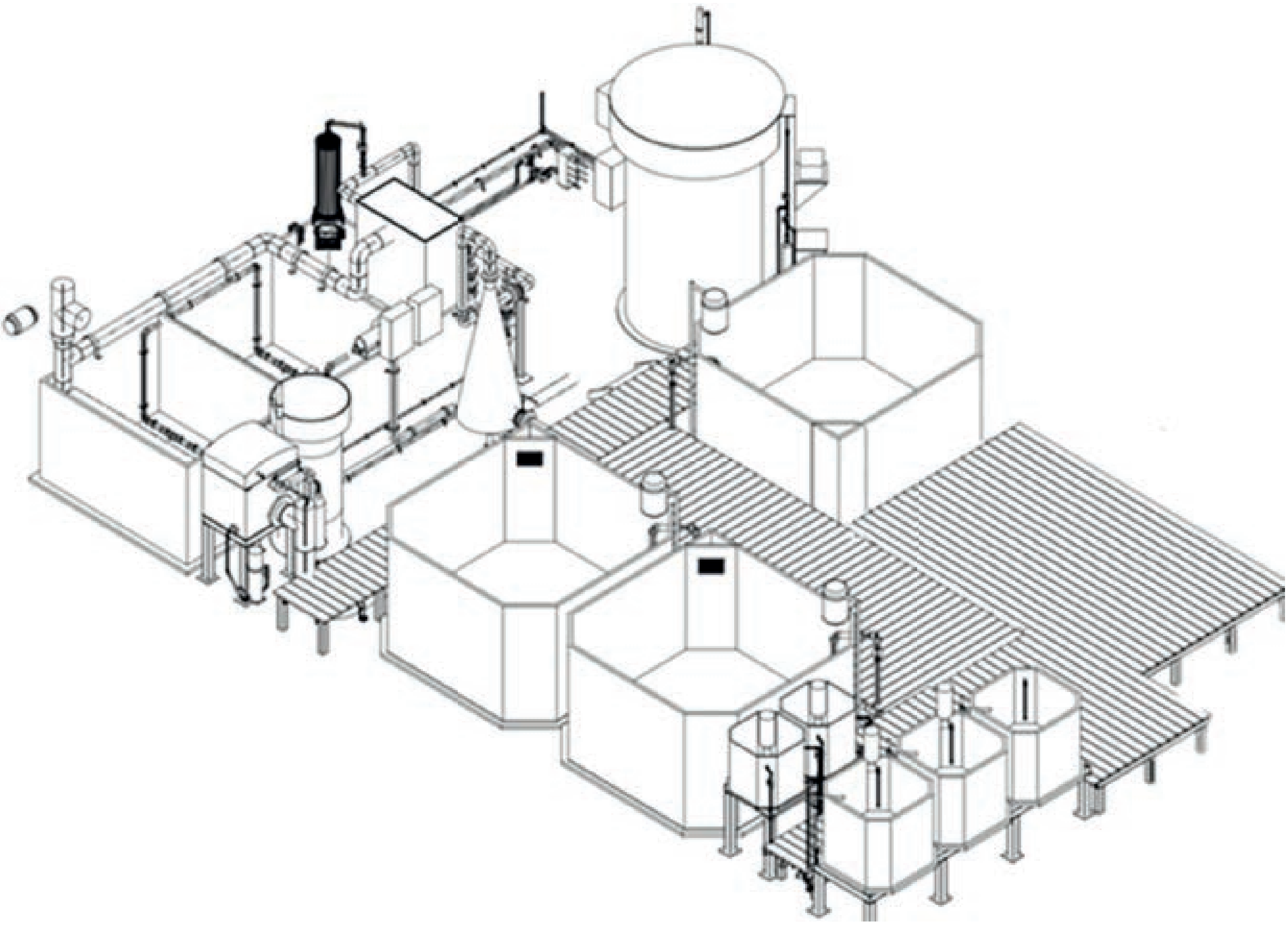

Figure 2 *Overview of the research recirculating aquaculture system for the GEOFOOD project. Source: Adapted from Landing Aquaculture.*

The system was designed as a 'miniature' commercial RAS, equipped with most filtration technologies that are used by modern commercial RAS farms. Figure 3 shows a layout indicating all major components such as the fingerling tanks (1), on-growing tanks (2), grow-out tanks (3), drum filter (4), nitrifying biofilter (5), CO_2 degasser (6), heat exchanger (7), circulation pumps (8), oxygen cone (9), ozone generator (10), pH dosing pump (11), denitrification reactor (12) and mineralization reactor (13). A full description of the RAS can be found in the design report by Landing Aquaculture, 2019.

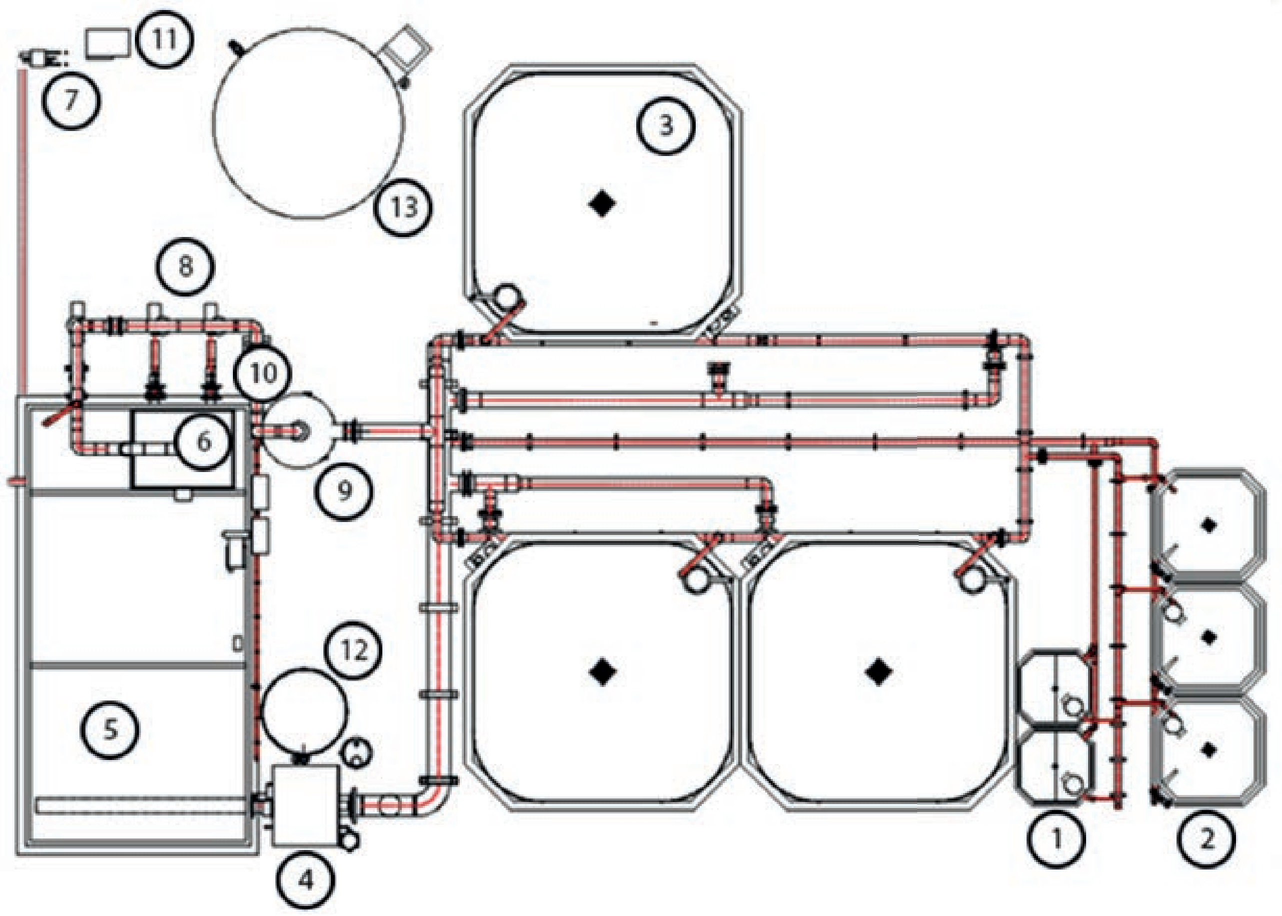

Figure 3 *Layout of all major system components of the RAS for the GEOFOOD project; fingerling tanks (1), on-growing tanks (2), grow-out tanks (3), drum filter (4), nitrifying biofilter (5), CO2 degasser (6), heat exchanger (7), circulation pumps (8), oxygen cone (9), ozone generator (10), pH dosing pump (11), denitrification reactor (12) and mineralization reactor (13). Source: Adapted from Landing Aquaculture.*

Figure 4 *The completed RAS, constructed by Landing Aquaculture within the greenhouse research facilities of Wageningen University & Research.*

Though the RAS was operational in May 2019, only data from the period September 16th 2019 until May 29th 2020 (i.e. 257 days) is used for the model validation in the present study. This is because some issues were encountered (e.g. loss of fish) during the start-up phase which affected the usability of the data. After the issues were solved a full growing cycle with tilapia was achieved, reaching stocking densities of >80 kg/m^3 and a feeding load of 20 kg/day.

Originally, the construction of the RAS was planned as an indoor facility (i.e. insulated building) instead of inside a greenhouse structure. Therefore, a few adaptations and assumptions had to be made for the model:

- Active ventilation was not controlled based on evaporation (e.g. relative humidity in the greenhouse) but was maintained at 800 m^3/h using an active duct fan.
- It is assumed that the amount of infiltration (i.e. passive air exchange) has a minimum of 0.05 times the greenhouse volume per hour and is increased with 0.1 for every m/s wind speed. The greenhouse vent positions are also taken into account.
- Heat loss through the roof of the greenhouse is based on an R-value of 0.6 m^2.K/W and a roof slope of 26°. The influence of wind and rain are not taken into account.
- Heat loss through greenhouse walls is based on an R-value of 0.7 m^2.K/W. Since the greenhouse walls do not have contact with the outside air, but with a corridor and two other compartments, the average air temperature on the other side of the walls is assumed to be equal to the outside air plus 6 °C with a minimum of 17 °C.
- Although the greenhouse is insulated with a reflective screen, it is assumed that 15% of the global radiation is absorbed by the greenhouse, acting as an ingoing flux of energy.

3.2 Sensors and measurements

To monitor energy flows going in and out of the RAS a network of sensors was installed. Each sensor provides data that is required to calculate the components of the system's energy balance:

$$Q_{demand} = Q_{building\ loss} + Q_{water\ exchange} + Q_{evaporation} + Q_{ventilation} - Q_{fish} - Q_{equipment} - Q_{radiation}$$

Q_{demand}	: overall heat demand of the RAS facility	[W/m^2]
$Q_{building\ loss}$	: heat loss from the building	[W/m^2]
$Q_{water\ exchange}$	: heat demand due to water exchange	[W/m^2]
$Q_{evaporation}$	: heat loss due to evaporation	[W/m^2]
$Q_{ventilation}$	: heat loss due to ventilation	[W/m^2]
Q_{fish}	: heat produced by the fish	[W/m^2]
$Q_{equipment}$	: heat produced by the equipment	[W/m^2]
$Q_{radiation}$	: heat gain from absorbing global radiation	[W/m^2]

Table 2 contains an overview of the type of sensors, where they were installed in the RAS and how the data contributes to calculating energy flows for model validation. All of the sensors were connected to a datalogger that automatically sent out the data every day to be stored on a server. After that the data is processed and added to a database on a regular basis. Besides the input from the sensors, the GEOFOOD database is supplemented with data from the weather station that belongs to the greenhouse research facilities in Bleiswijk. Another source of data is the greenhouse climate computer that provides for instance vent- and screen positions as well as heating pipe temperatures.

The only energy balance component that could not be measured directly nor calculated based on measured data was the heat produced by the fish. This energy flow is estimated according to the feeding schedule (see Equation 6).

Table 2
List of installed sensors and their application for the validation of the aquaponic energy model.

Sensor type	Description	Input for energy balance component
Energy meter	Installed at the RAS water heat exchanger	Q demand
Water temperature	Installed at the pipe space heating system	Q demand
Air temperature	Measures the temperature of the air within the RAS compartment	Q building loss, Q evaporation
Relative humidity	Measures the relative humidity of the air within the RAS compartment	Q building loss, Q evaporation
Water flow meter	Installed at the supply water pipe	Q water exchange
Water temperature	Installed at the supply water pipe	Q water exchange
Water flow meters	Installed at all water output pipes (i.e. fertigation and sewage)	Q water exchange, Q evaporation
Water temperature	Measures RAS water temperature and also functions as input for heating system control	Q water exchange, Q evaporation
Air temperature	Measures the temperature of the air within the CO_2-degasser ventilation pipe	Q ventilation
Relative humidity	Measures the relative humidity of the air within the CO_2-degasser ventilation pipe	Q ventilation
Energy counters	Installed at all electrical groups for equipment (e.g. pumps and drum filter)	Q equipment
Global radiation	Installed at the weather station	Q radiation
Air temperature	Measures the temperature of outdoor air	Q building loss, Q ventilation
Relative humidity	Measures the relative humidity of the outdoor air	Q building loss, Q ventilation
Windspeed	Measures outdoor windspeed	Q building loss

3.3 Validation methods

To validate the model two approaches are used. First, the overall heat demand as calculated by the model, based on the input data, is compared to the measured heat demand. The measured heat demand is obtained from the meter that recorded the energy used by the RAS heat exchanger plus the calculated pipe space heating based on the recorded pipe temperatures. The calculated heat demand uses data input from all the other sensors in Table 2 and the equations in Chapter 2. This validation approach is therefore based on the equation:

$$\begin{aligned} Q_{demand} &= Q_{heat\ exchanger} + Q_{pipe} \\ &= Q_{building\ loss} + Q_{water\ exchange} + Q_{evaporation} + Q_{ventilation} - Q_{fish} - Q_{equipment} - Q_{radiation} \end{aligned}$$

The second approach compares the sums of the ingoing and outgoing energy flows. This gives more insight into the role of individual energy flows and allows for some targeted model calibration. This validation approach is based on the equation:

$$Q_{heat\ exchanger} + Q_{pipe} + Q_{fish} + Q_{equipment} + Q_{radiation} = Q_{building\ loss} + Q_{water\ exchange} + Q_{evaporation} + Q_{ventilation}$$

For both approaches the R^2 and mean squared error (MSE) are calculated.

4 Results

Figure 5 shows the daily average calculated heat demand and the measured heat demand per m^2 RAS. R^2 equals 85% and MSE is 172.

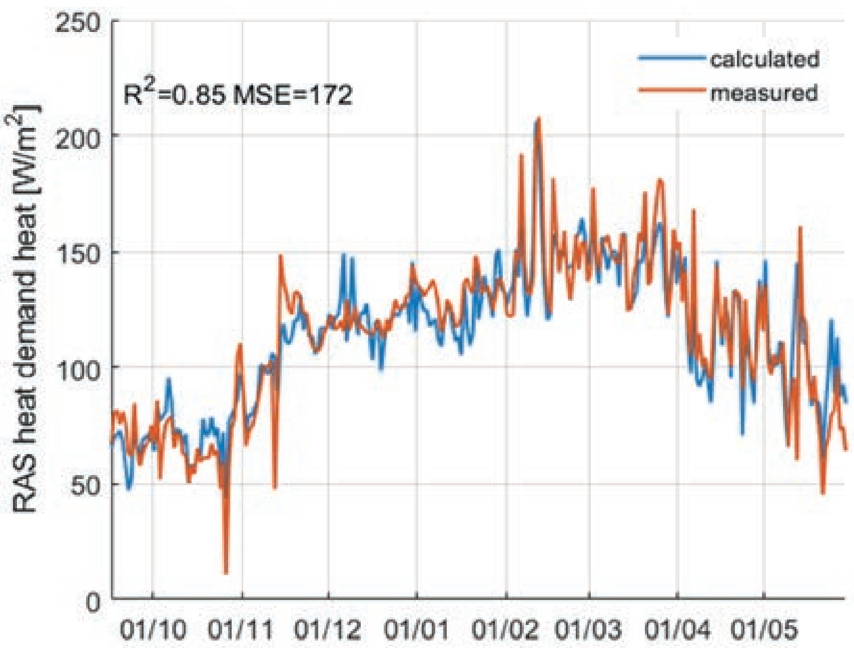

Figure 5 *Daily average calculated and measured heat demand per m2 RAS.*

To inspect the individual ingoing and outgoing energy flows, these are plotted in Figure 6 and 7 respectively. From such overviews it can be seen that evaporation is responsible for most heat loss. Evaporation does seem rather constant (also in summer) which suits the consistent character of geothermal heat supply. Then again, it can also be interpreted that measures should be taken to reduce heat loss due to evaporation. Heat loss through walls, roof and floor show more dependency on the outdoor climate, but the amplitude of the fluctuation is less than that of a greenhouse. The amplitude would likely decrease further if the RAS would have been constructed within an opaque building instead of a screened greenhouse structure. Some peaks can be seen in heat use due to water exchange. In summer this is not an issue for the geothermal heat supply, in wintertime it may prove difficult as other facilities connected to the geothermal well, such as a greenhouse, also need heating.

In terms of heat input, most was supplied by the heat exchanger (heating the fish water) and some by pipe heating (heating the facility air). Both systems could be supplied with high- and low temperature geothermal heat. Most efficient would be to heat the fish water via a heat exchanger because water has a much higher heat capacity than air. The heating temperature that was used during the experiments ranged between 35-45 °C, which indicates that the RAS could be supplied with residual heat coming from a greenhouse heating system and high temperature heat directly from a geothermal well is not necessarily required at all times.

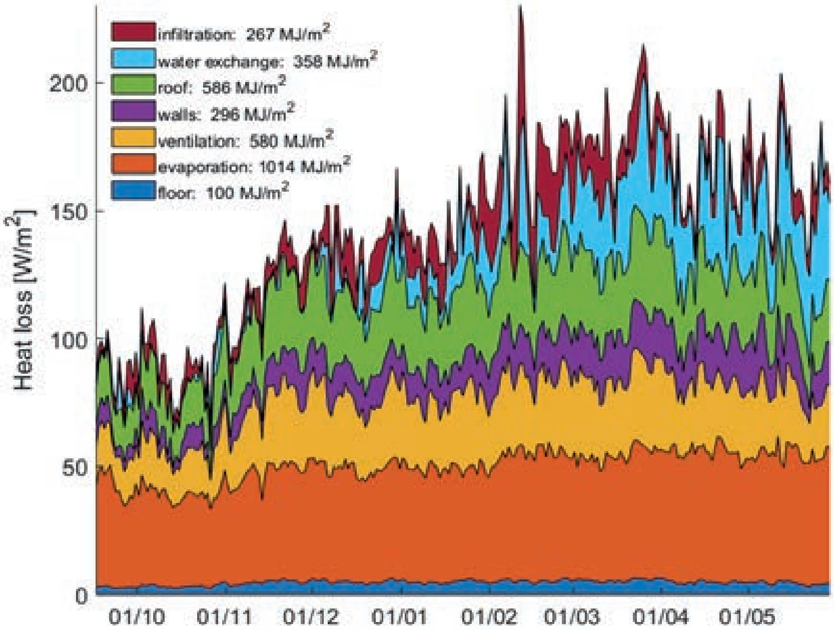

Figure 6 *Outgoing energy flows.*

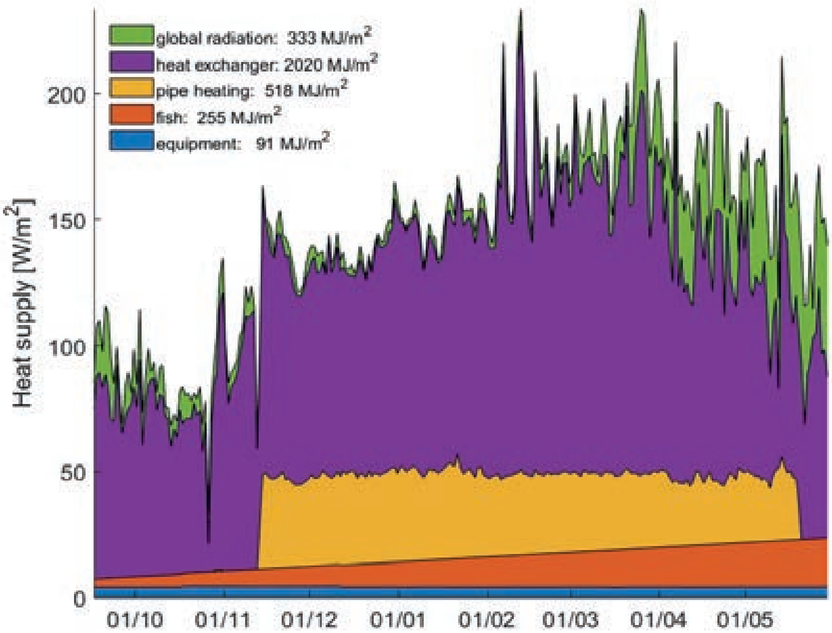

Figure 7 *Ingoing energy flows.*

If the model correctly calculates all energy flows in the system, the ingoing flows should be equal to the outgoing flows. Therefore, the validation can also be approached by comparing the sums of all ingoing and outgoing flows as can be seen in Figure 8. For this approach R^2 equals 88 % and the MSE is 172.

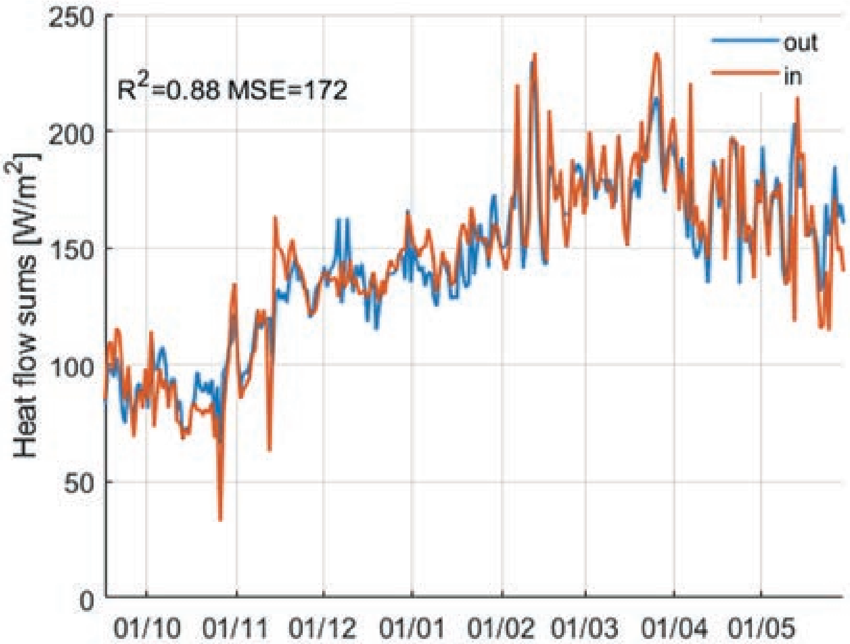

Figure 8 *The sum of outgoing flows compared to the sum of ingoing flows.*

5 Discussion and conclusions

The results show a reasonable correlation between the calculated and measured heat demand. However, a number of uncertainties remain that may affect the quality of this validation study. As explained in Chapter 2 some assumptions had to be made, mainly due to the change in construction site; from a RAS in an insulated building to a greenhouse compartment. As a result:

- The R-values of the roof and walls were not measured but estimated.
- The temperature outside the walls (i.e. greenhouse corridor and surrounding compartments) had to be roughly estimated.
- The heat loss to the floor might be overestimated because the greenhouse is not in an open field, but built in between other greenhouse compartments.
- The amount of global radiation that is absorbed by the roof is an estimate, partly based on model calibration.
- The calculation of the infiltration does not take into account the possible influence of the active ventilation; a fan continuously blowing air out. This fan might cause a pressure difference that affects the passive infiltration.

Furthermore, only the total heat demand could be validated, but not individual heat flows. This might lead to a 'correct answer for the wrong reasons'. For example, the influence of evaporation may be overestimated while global radiation is underestimated leading to a calculated total heat demand that is close to the actual heat demand, but not because the underlying model is correct.

Though the RAS at the research facilities from Wageningen University & Research is set up as a high-tech system and functions as a 'miniature' commercial farm, only about 22% of the available space (32 m^2/144 m^2) is taken up by fish tanks. When scaling up to a fully commercial fish farm, the ratio between space needed for equipment and space available for fish tanks may shift. As a rough rule of thumb the area covered by fish tanks and RAS tanks (e.g. biofilter and sump) can approach 30-35%. For the energy flows this shift would mean that heat losses due to evaporation, ventilation and water exchange increase per m^2 while heat loss by infiltration, roof, walls and floor remain the same. Therefore, to achieve energy efficient (indoor) aquaculture, the focus should be placed on lowering evaporation and ventilation (or recovering energy from these flows) as these are the major modes of heat loss.

Overall, the model seems capable of estimating a correct 'order of magnitude'. The achieved model accuracy therefore supports the underlying goal within the GEOFOOD project; to estimate the additional heat that can be extracted from a geothermal well by a RAS that uses (low temperature) residual heat. For geothermal regions that seek solutions towards sustainable energy use, the model can be applied to estimate the heat demand of a RAS in different climates and for different designs and fish species. The general heat use pattern throughout the year may especially be of value if the RAS is to be integrated within a larger food production system that utilizes (cascaded) geothermal energy. The model may also be used to optimize the scale of a RAS in relation to other heat utilization processes in order to maximize the heat use efficiency of geothermal installations. These applications all aim to provide valuable insights into setting up viable business cases for food production systems utilizing geothermal energy. For instance, the model has been used by Boedijn, Baeza, et al. 2019b, to estimate that a 6500 m^2 RAS can be sustained by the residual heat of a 5 ha geothermally heated tomato greenhouse, located in the Netherlands, increasing geothermal energy use by 31%.

Additionally, some effects of design choices on individual heat flows within RAS may also be examined using the model. For instance, it is clear that heat demand can be significantly lowered if the evaporation could be reduced by means of tank covers or otherwise recovered. The model may not be suitable if more precise simulations are required, looking into fluctuations on an hourly basis. For that, certain RAS management actions such as exact feeding times and -amounts would have to be integrated into the model. Further validation based on datasets from other RAS facilities would of course also contribute to a more robust model.

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