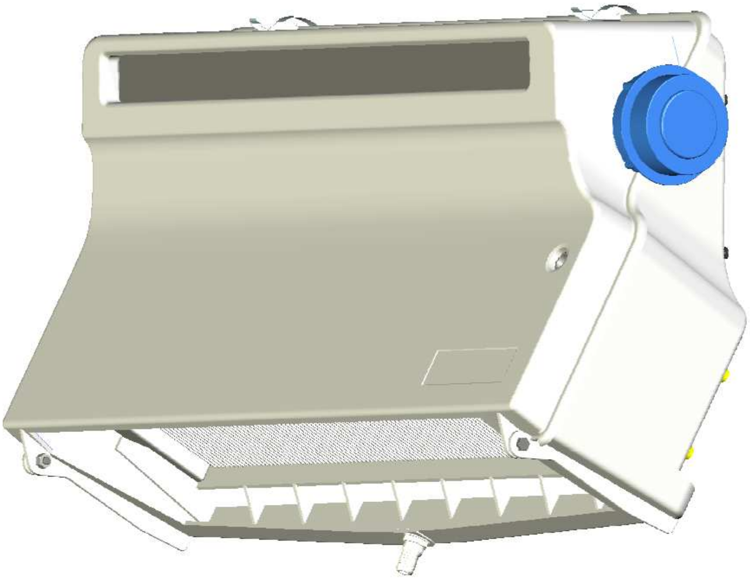
Transfer capacity of the OPAC106 heat exchanger



H.F. de Zwart
H.J.J. Janssen

Wageningen University and Research
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Wageningen UR Glastuinbouw

Adres : Droevendaalsesteeg 1, 6708 PB Wageningen
: Postbus 16, 6700 AA Wageningen
Tel. : 0317 - 48 60 01
Fax : 0317 - 41 80 94
E-mail : glastuinbouw@wur.nl
Internet : www.glastuinbouw.wur.nl

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1 Summary

In recent years, the search for ways to control greenhouse climate more accurately and the need for low temperature heating systems have been driving forces for the developments in heat exchangers for horticulture. There are systems that are placed up high in the greenhouse and systems that are located lower to the ground. There are installations with slurves that distribute the air through the greenhouse and also systems with a free air flow. Because of the multitude of applications, comparisons of heat exchangers are difficult.
In greenhouses with movable benches there is much space at floor level, enabling to locate voluminous heat exchangers beneath the benches. Other greenhouse lay-outs don't have this space at the floor. Then cooling units can be mounted up high, but then light interception becomes important. Then the dimensions are an important quality characteristic of the cooling unit.
Moreover, the design of the heat exchange system will affect the uniformity of the horizontal and vertical temperature distribution. Therefore, when comparing different systems, the effects on temperature distribution have to be taken into account.
Finally there is also a big difference in noise level between heat exchangers.

In this report, the heat transfer performance of a new type of compact heat exchanger is studied, the OPAC106 heat exchanger with cross flow fan. OPAC means Oval Pipe Air Conditioner and refers to the construction of the heat exchanging part of the unit where oval pipes contribute to a good air flow. The output of this exchanger, when used in hot and humid greenhouses, is in the range of 20 kW per unit. Of course the ultimate power in practice is very much determined by the conditions of use. If the cooling water is very cold (*e.g. 4 °C)* the cooling power of the unit will be more, and when used in dry air or low greenhouse temperatures the cooling capacity will be less.

The measurements used for benchmarking of the OPAC 106 heat exchanger therefore cover various temperatures and humidity. Apart from the fact that these tests give a good overview of the cooler performance, the data generated has been used to develop a simulation model that describes the cooler's performance under arbitrary conditions. With this model also a reliable expectation of the heat exchanger performance in heating mode can be made.

However, the displayed performance of the OPAC 106 heat exchanger does not give so much information as long as it's not compared to the performance of alternatives. This is why in this report the opac106 heat exchanger is initially compared with the FiWiHEx heat exchanger as designed and built in 2008. Because this production series of FiWiHEx heat exchanger has almost the same dimensions and was developed for the same performance range, the comparison could take place in a simultaneous test. This comparison enables a test in exactly the same conditions.
From this simultaneous test it was shown that the opac106 heat exchanger performed better, especially when looking at the electrical consumption per unit of cooling power.

The higher heat transfer efficiency reduces the noise level of the OPAC 106 heat exchanger because in general the fan can at a lower speed as compared to comparable coolers..It was also noted that the OPAC 106 heat exchanger has a lower water pressure drop than the FiWiHEx heat exchanger. The effects of sound level and the water pressure drop are however not quantified.

In addition to the detailed comparison with the FiWiHEx heat exchanger the performance of the OPAC 106 heat exchanger is compared to yet another heat exchanger for cooling application in the same category. Also in relation to this other design, the OPAC 106 heat exchanger achieves better results. With the fact that in a heavily cooled semi-closed greenhouse the electricity consumption for the fans during cooling is approximately 15 kWh per m² per year, the improvement of the heat transfer of the OPAC 106 calculates a savings on electricity consumption of 5 kWh per m² per annum. If the heat exchanger is also used for heating then the savings by the application of an OPAC 106 heat exchanger in comparison with the two alternatives goes up to 8 kWh per m² per year.

2 Introduction

Cooling of greenhouses is a technology which is very actively being developed. The use of cooling can improve the quality and quantity of production in the greenhouse. It also may be used to collect energy from summertime heat-surpluses, to serve as an energy source during cold periods. This enables the application of heat pumps which can contribute to a decrement in the primary energy use of greenhouses.
For a robust and economically relevant performance it is important that the heat exchangers used for cooling and heating the greenhouses have a high heat transfer per unit of driving power for the air and water circulation, combined with limited investment costs for the exchangers.

In this report a new type of heat exchanger for horticulture is assessed. It is a compact heat exchanger which is built from a combination of a cross flow fan and an OPAC106 tube-and-fin exchanger. These heat exchangers can be used to cool a greenhouse surface area of 50-100 m² per unit, but they can also be used for low-temperature heating. In that case, one unit, can provide a base heating of about 50 W/m² for approximately 160 m² of greenhouse.

Chapter 3 discusses an experimental setup that generated a number of benchmark points. These points apply to the cooling capacity in wet and dry conditions with relatively high greenhouse temperatures (25 to 28 ° C) and low cooling water temperatures (7 to 8 ° C). In Chapter 4 a model is discussed which computes the performance of the cooler under arbitrary conditions. This model was calibrated with the benchmark points obtained and appeared to match the measured data very well. Since the model fully takes sensible and latent heat exchange into account, the model can olso be used to generate sound expectations for the heat exchanger in heating mode.

In chapter 5 the performance of the OPAC106 heat exchanger is compared to two other heat exchangers.The most extensive comparison is made with the FiWiHEx heat exchanger which has the greatest similarity with respect to dimensions and capacity range.

In chapter 6 the conclusions from this study are presented and placed into the context of everyday use.

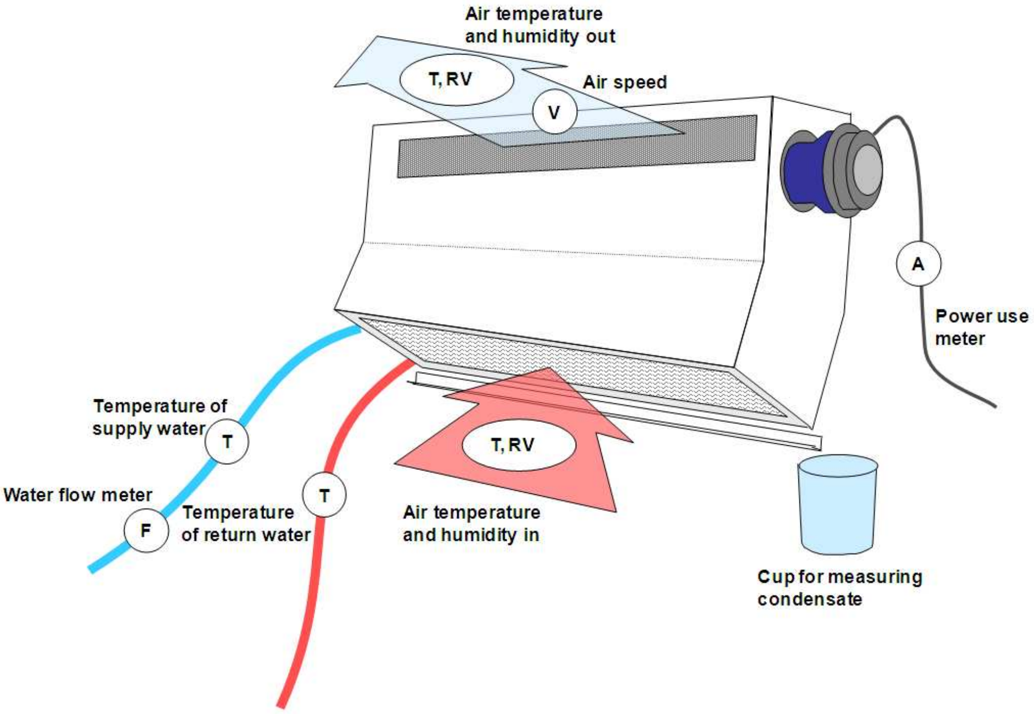
The present report does not address the performances in terms of horizontal and vertical temperature distribution in the greenhouse. Also, the resistance to corrosion is not included in the study. Both points are at least as important as the heat transfer performance, but examined in a follow-up project.

3 Measurements of the heat exchanger OPAC106

3.1 Measuring system

The capacity of a heat exchanger is determined by device characteristics and the conditions of its use. The device characteristics are determined by the efficiency of the heat exchanging surface and the electrical efficiency of fan that drags the air through the device. In addition, the operating conditions have a significant influence. In moist air, the same cooling unit will provide a larger cooling capacity than in dry air. Also, when increasing the water flow and / or air flow through the heat exchanger the heat transfer will increase.

To determine the performance of the OPAC 106 heat exchanger a large number of data points collected were collected under different circumstances. In the sketch below, the set up of the measurements around the heat exchanger are shown schematically.



Figuur 1. Sensors around the OPAC 106 heat exchanger

To record and store the measurements the TCS (Total Control System) measurement and control system from Lek / Habo was used.
Before beginning the measurements the temperature sensors of the supply and return water were held side by side in a bucket of water for a while to determine whether they record the same temperature. This was the case, apart from a noise of ± 0.1 ° C, so later, the measured differences between supply and return temperature could be regarded as reliable. The water flow was determined with a turbine flow meter, which readout was compared with an inductive, calibrated, flow meter. This also led to the conclusion that the flow was measured correctly. The combination of these three measurements yielded an accurate actual cooling power measurement..

The air movement measurements were compared with findings from a sensor network mounted at the air inlet and outlet side of the cooling unit. The power consumption of the fan was determined by a current meter included in the circuit, which after multiplication by the stable voltage of 230 V indicates the power consumption.

The condensation rate was determined by collecting the water that runs out of the unit per 5 minutes (measured with a stopwatch). These measurements started not before 7 minutes after the fan revolution rate was changed, in order to ensure that the working conditions were stabilized.

To determine the operating conditions of the heat exchanger, the ingoing air temperature and humidity were constantly measured. Here a temperature and humidity sensor were placed in front of the air intake of the heat exchanger. The outgoing air temperature and humidity are also measured.

To determine the average air flow through the exchanger, the out going air speed was measured at 5 distinct locations along the outlet side. This yielded an average speed which, multiplied by the effective area of the fan (0.083 m2), resulted in an effectieve air flow rate.

Figure 2 shows a photograph of the setup in a greenhouse test facility of the PTC+ training centre in Ede (the Netherlands). The heat exchanger which was used consists of the type of fan and heat exchanger block intended for later use, but not yet in its final commercial casing. In fact, the final casing was partly based on the experiences during the measurements at PTC+. The selected angle at which the heat exchanger was placed appeared to be satisfactory. The condensate run off easily towards the gutter intended to drain the cooler and the heat exchanger never became saturated with water.

The test area at PTC+ was an empty greenhouse compartment of 200 m² where the humidity was maintained at a high level by a mist system and in which the sun and a heating system provided the high temperatures.

In its final form, the OPAC 106 will have a removable plastic casing so that the heat exchanger can be opened for inspection and/or cleaning.

Figuur 2. Measuring system in greenhouse compartment from PTC+ in Ede (the aluminum foil was to shade the temperature sensors from the influence of direct sunlight).

3.2 Results

The measurements were carried out on Monday 13th and Thursday, 15th of April 2010. Both days were sunny, so not much artificial heating was needed to bring the greenhouse air temperatures between 25 and 28 ° C.

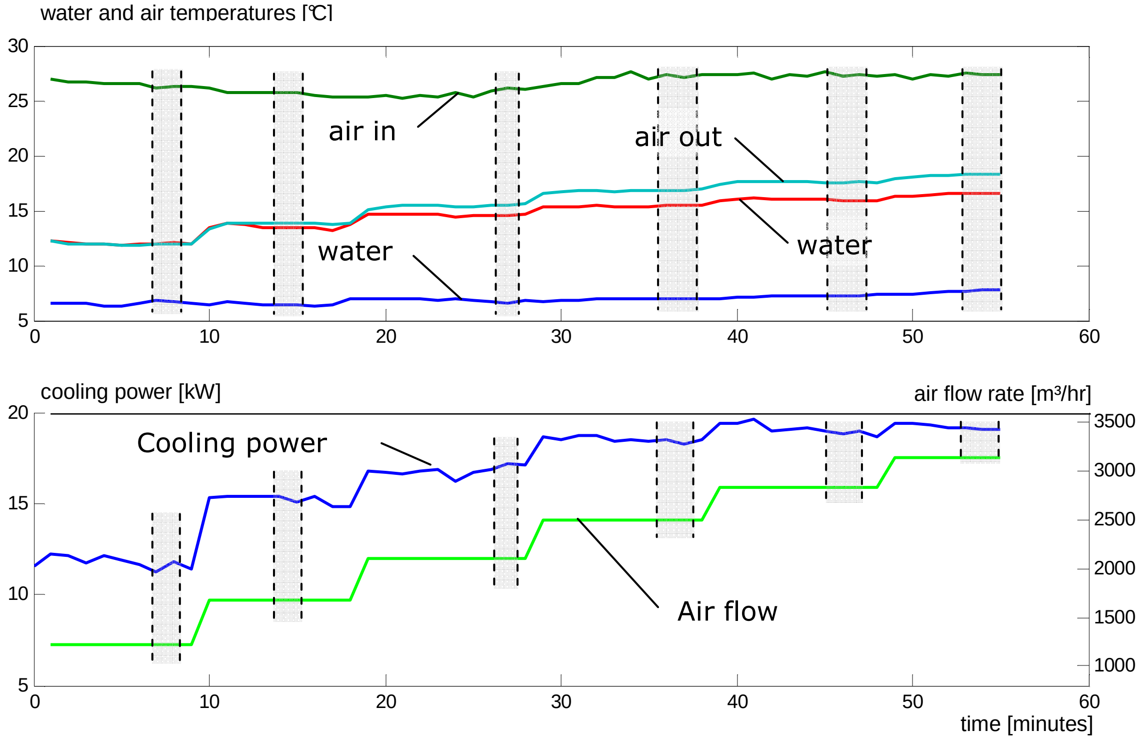
Figure 3 shows the results of a series of measurements. A series of measurements consisted of one cycle of 6 to 8 levels with a constant flow of cooling water and approximately a constant humidity and greenhouse temperature to allow the heat exchanger to work with different airflows.

The measurements took place continuously, but the measurements on which the benchmark points are based are the averages of the displayed small grey areas in the graphs. The selection of these small areas was done manually by looking closely at the graphs and selecting those areas where all the values' lines were as constant as possible.

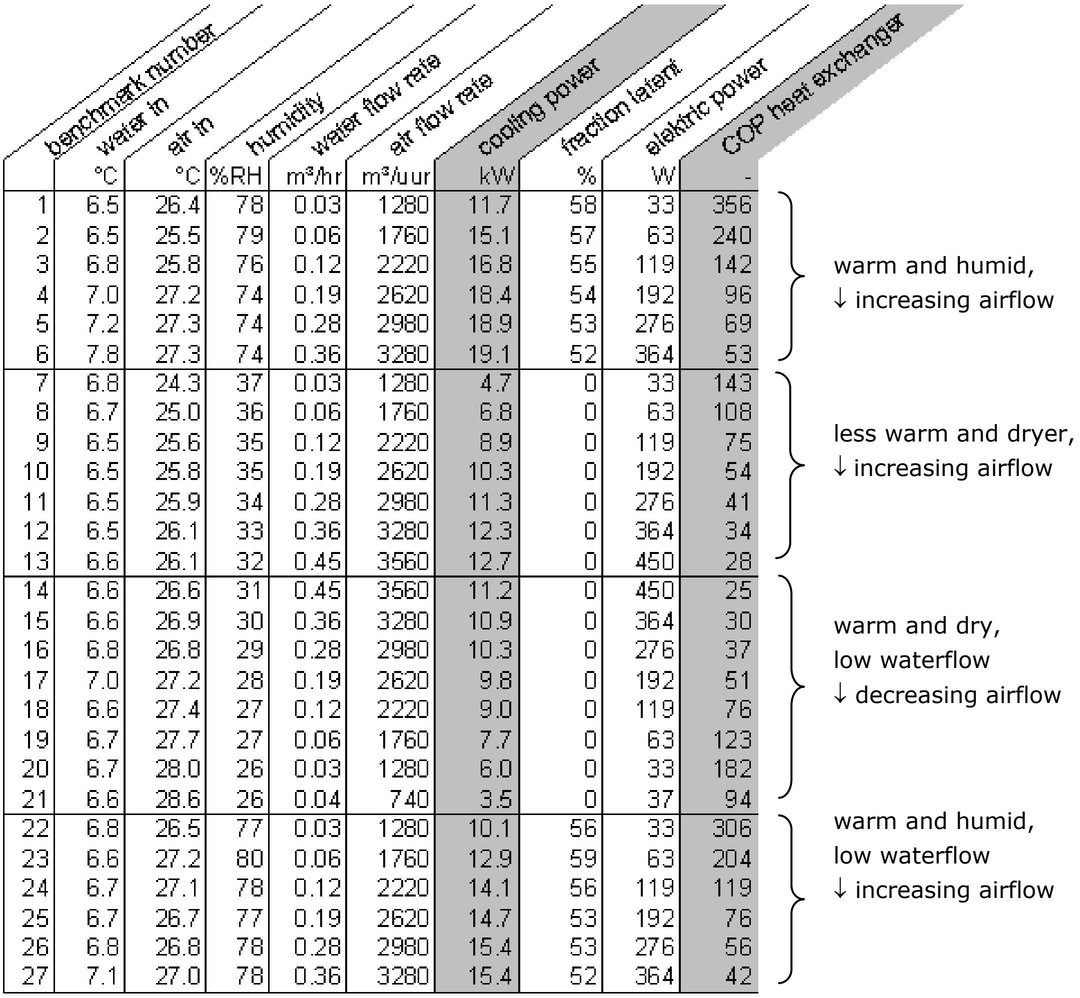
Similar to the procedure sketched in Figure 3, a total of 27 benchmark points were obtained. These are shown in the table of Figure 4. The maximum cooling capacity measured during this period was 19.1 kW, which was achieved with a high water flow, high air flow and a high humidity.

An high humidity is an important contributor to the cooling power because, as the table shows, more than half of the cooling capacity comes from latent heat. This effectively doubles the cooling surface, because the same surface exchanges heat and moisture.

Besides the cooling capacity, the table also shows the electrical power consumption. When dividing the electrical power by the cooling capacity a Coefficient of Performance (COP) can be defined. It is clear that the COP is high at a low load of the cooler and decreases to values between 25 and 50 at the maximum water and air flow.



Figuur 3. Ingoing water and air temperatures and cooling capacities measured at different air flow rates. The RH during these measurements was between 79% (at the beginning of the hour) and 74% (at the end of the hour). In the graph, 6 stationary areas are marked whose average values are used as a benchmark point. The water flow in this test series was 1.87 m³/hour.



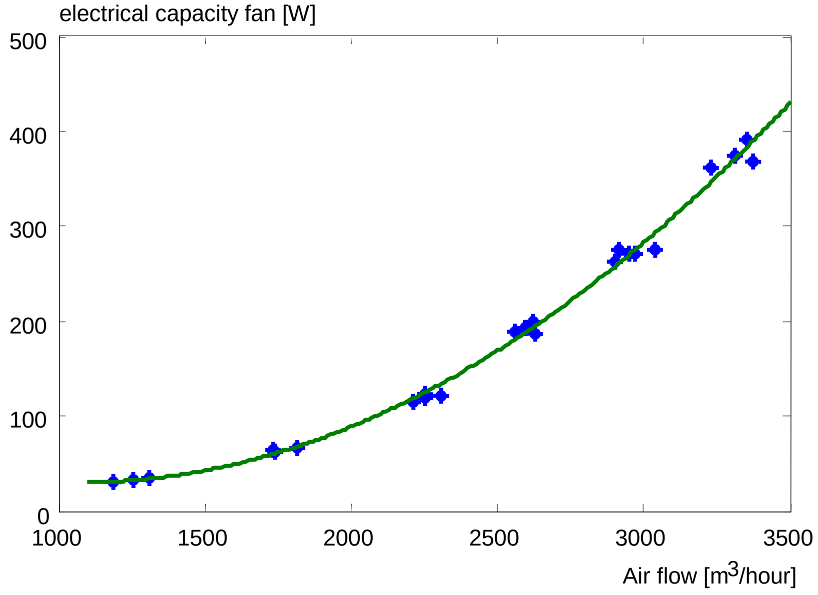
benchmark number	water in °C	air in °C	humidity %RH	water flow rate m³/hr	air flow rate m³/uur	cooling power kW	fraction latent %	elektric power W	COP heat exchanger -	
1	6.5	26.4	78	0.03	1280	11.7	58	33	356	warm and humid, ↓ increasing airflow
2	6.5	25.5	79	0.06	1760	15.1	57	63	240	
3	6.8	25.8	76	0.12	2220	16.8	55	119	142	
4	7.0	27.2	74	0.19	2620	18.4	54	192	96	
5	7.2	27.3	74	0.28	2980	18.9	53	276	69	
6	7.8	27.3	74	0.36	3280	19.1	52	364	53	
7	6.8	24.3	37	0.03	1280	4.7	0	33	143	less warm and dryer, ↓ increasing airflow
8	6.7	25.0	36	0.06	1760	6.8	0	63	108	
9	6.5	25.6	35	0.12	2220	8.9	0	119	75	
10	6.5	25.8	35	0.19	2620	10.3	0	192	54	
11	6.5	25.9	34	0.28	2980	11.3	0	276	41	
12	6.5	26.1	33	0.36	3280	12.3	0	364	34	
13	6.6	26.1	32	0.45	3560	12.7	0	450	28	
14	6.6	26.6	31	0.45	3560	11.2	0	450	25	warm and dry, low waterflow ↓ decreasing airflow
15	6.6	26.9	30	0.36	3280	10.9	0	364	30	
16	6.8	26.8	29	0.28	2980	10.3	0	276	37	
17	7.0	27.2	28	0.19	2620	9.8	0	192	51	
18	6.6	27.4	27	0.12	2220	9.0	0	119	76	
19	6.7	27.7	27	0.06	1760	7.7	0	63	123	
20	6.7	28.0	26	0.03	1280	6.0	0	33	182	
21	6.6	28.6	26	0.04	740	3.5	0	37	94	
22	6.8	26.5	77	0.03	1280	10.1	56	33	306	warm and humid, low waterflow ↓ increasing airflow
23	6.6	27.2	80	0.06	1760	12.9	59	63	204	
24	6.7	27.1	78	0.12	2220	14.1	56	119	119	
25	6.7	26.7	77	0.19	2620	14.7	53	192	76	
26	6.8	26.8	78	0.28	2980	15.4	53	276	56	
27	7.1	27.0	78	0.36	3280	15.4	52	364	42	

Figuur 4. The 27 benchmark points for the characterization of the OPAC 106 heat exchanger

Although the heat transfer performance of the OPAC 106 heat exchanger can be described as good, the comparison with other heat exchangers cannot be made quickly because it very much depends on the operating conditions.

Therefore, a simulation model was developed so that from the benchmark points the behaviour of heat exchanger can be deduced and a reliable statement on the performance in any conditions can be obtained. This model is presented in the next chapter.

As can be seen in the table of Figure 4, in addition to the heat transfer the electrical performance of the fan was measured. An analysis of the relationship between air flow and electricity demand is shown in the chart below.



Figuur 5. Relation between airflow and electricity use for the OPAC106 heat exchanger

In the range of 1100-3500 m^3/hr of air flow, the electric power consumption can very well be described with a quadratic function.
The equation reads:

Electric power = 6.7e-5 flow^ 2 – 0.145 flow + 107 [W] (1100 m^3/hr <flow <3500 m^3/hr)

In this equation, the air flow is expressed in m^3/hr and the result is an electric power consumption in Watts. The ventilator is a 230 volt motor with a digital speed control and a range of 0 and 100%. However, experience shows that the practical control range is between 30 and 80%. Moreover, at low air flow, the homogeneity of air distribution in the horizontal plane will be negatively affected. Consequently, none of the measurements were at velocity settings below 30%. .
The endpoint of the displayed graph is the maximum air flow through the fan.

Figuur 6. Detail photo of fan motor of the OPAC 106 heat exchanger

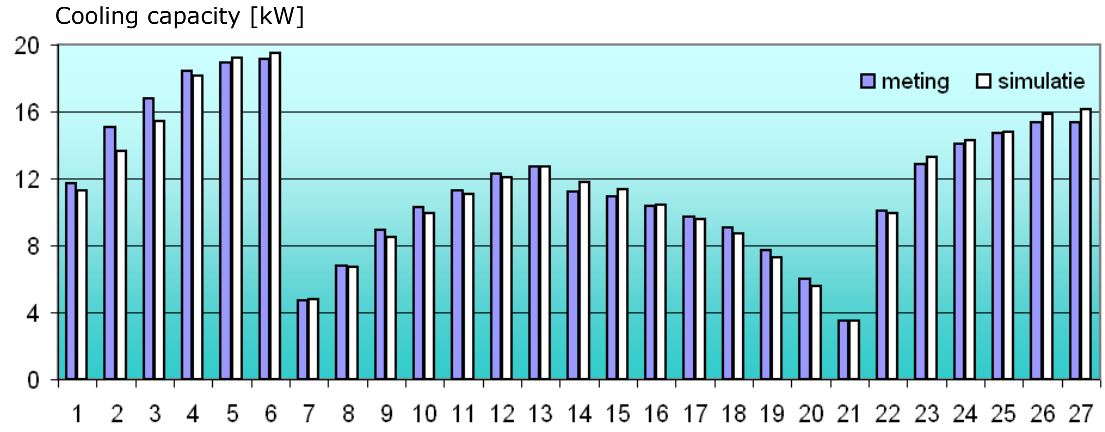
4 A simulation model for the translation of benchmark points to arbitrary conditions

In a heat exchanger there are two mass flows (in this case water and air) that are separated by means of good heat conducting material. This keeps the mass flows separated, but the heat can be exchanged.

The heat exchange capacity is a direct result of the temperature difference between the two mass flows and is affected by the transfer coefficients at both the air and water side.
These transfer coefficients are not constant. At a high air and/or water flow, the turbulence along the exchange surfaces increases, so the exchange works better. This gives a heat exchanger a typical non-linear behavior (twice as much air through the heat exchanger does not just double its power).

Another important source of non-linearity is condensation, when used in the cooling mode. Condensation occurs when a surface temperature is below the dew point and the rate at which condensation occurs depends on the vapour pressure difference between air and surface. Vapour pressure relations are highly non-linear so a cooling unit under drier conditions performs much less than in humid conditions.
In the model, built bij Wageningen UR Horitculture, all these aspects to take into account based on the underlying physics[1]. Besides some geometrical parameters, this model has three tuning parameters which can be determined by an automated parameter-search method**..**

The figure below shows the comparison between the 27 measured and simulated cooling capabilities of the OPAC 106 heat exchanger.



Figuur 7. Comparison of simulation results with the measured 27 benchmark points of the heat exchanger OPAC106 Meting = measurement, simulatie = simulation

The comparison shows that with the exception of the second and third benchmark point, where the deviation is almost 10%, the simulation model shows a good representation of the realized cooling capacities of the OPAC 106 heat exchanger under specific conditions.
The simulation model, parameterized for the OPAC 106 heat exchanger, is available so that the cooling capacity for any situation can be calculated.

Figure 8 shows the input and output of the spreadsheet. It appears that the OPAC106 heat exchanger under the operating conditions shown below, realizes a cooling power of 22.9 kW and a dehumidification

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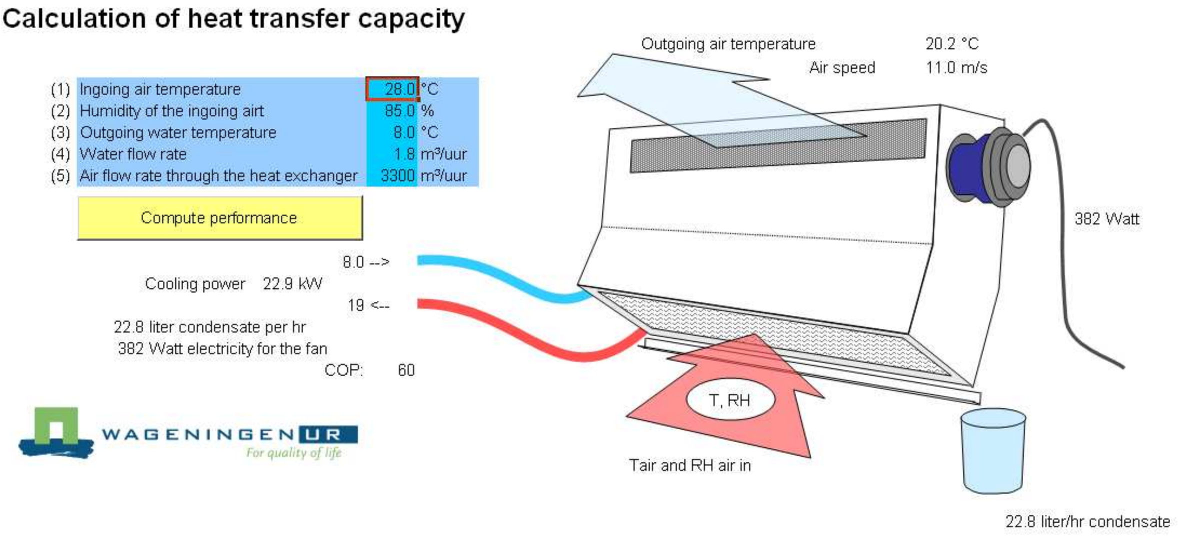
[1] 1.Zwart, H.F. de and F.L.K. Kempkes, 2008, Characterizing of Cooling Equipment for Closed Greenhouses, Acta horticulurae (2008)801, pag 803- 811

of 22.8 lit/hr of (the condensate rate). The heat exchanger provides 60 W of cooling power per Watt electricity applied.



Calculation of heat transfer capacity

(1) Ingoing air temperature 28.0 °C
(2) Humidity of the ingoing airt 85.0 %
(3) Outgoing water temperature 8.0 °C
(4) Water flow rate 1.8 m³/uur
(5) Air flow rate through the heat exchanger 3300 m³/uur

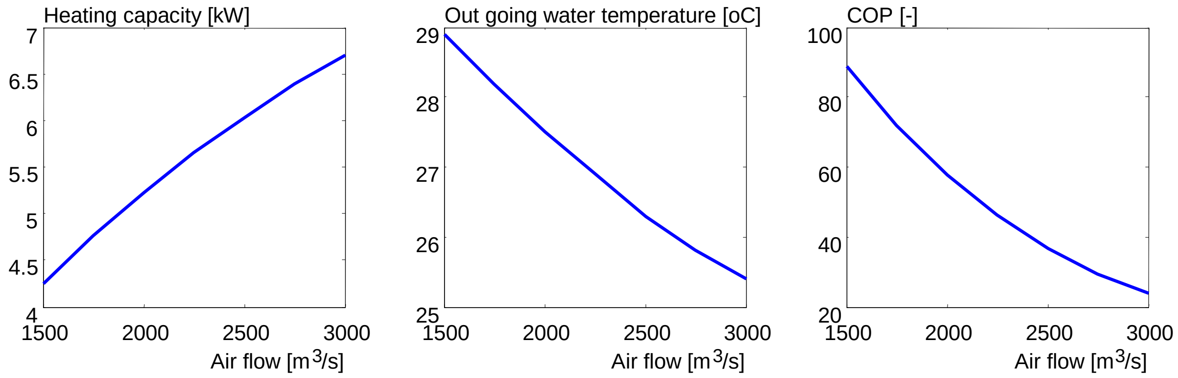
Compute performance

8.0 -->
Cooling power 22.9 kW
19 <--
22.8 liter condensate per hr
382 Watt electricity for the fan
COP: 60

Figuur 8. Input and output of the OPAC106 heat exchanger model

The simulation model includes the contribution of latent and sensible heat transfer, and therefore the model’s calculations can be used for both the cooling mode and the heating mode.

Figure 9 shows the heat output if the heat exchanger is used to heat air to maintain 20 °C with heating water at 35 °C. The water flow rate is set at 0.6 m³/hr and the air flow goes from 1500 to 3000 m³/hr. The figure shows not only the supplied heating power, but also the return water temperature and the COP of the heat exchanger in the conditions specified.



Figuur 9. Simulated performance of the OPAC106 heat exchanger in heating mode. The greenhouse temperature is 20 °C, the heating water temperature is 35 °C and the water flow rate is 0.6 m³/hr.

The heating power can of course be increased by increasing the temperature or the flow rate of the supply water, but in both these situations the outflow water temperature would increase. At a flow rate of 1.8 m³/hr and an air flow of 3000 m³/hr a supply water temperature of 35 °C will give over 8.5 kW heating power, but then the return water temperature is nearly 31 ° C.

5 The OPAC106 heat compared with other heat exchangers

The analysis of the OPAC106 heat exchanger have given interesting results, but the data obtained does not mean much if they are not compared to the heat transfer performance of more or less similar cooling units. Therefore, parallel to the evaluation of the OPAC106 heat exchanger, the same setup and measurements were made for FiWiHEx heat exchanger assembled in 2008.

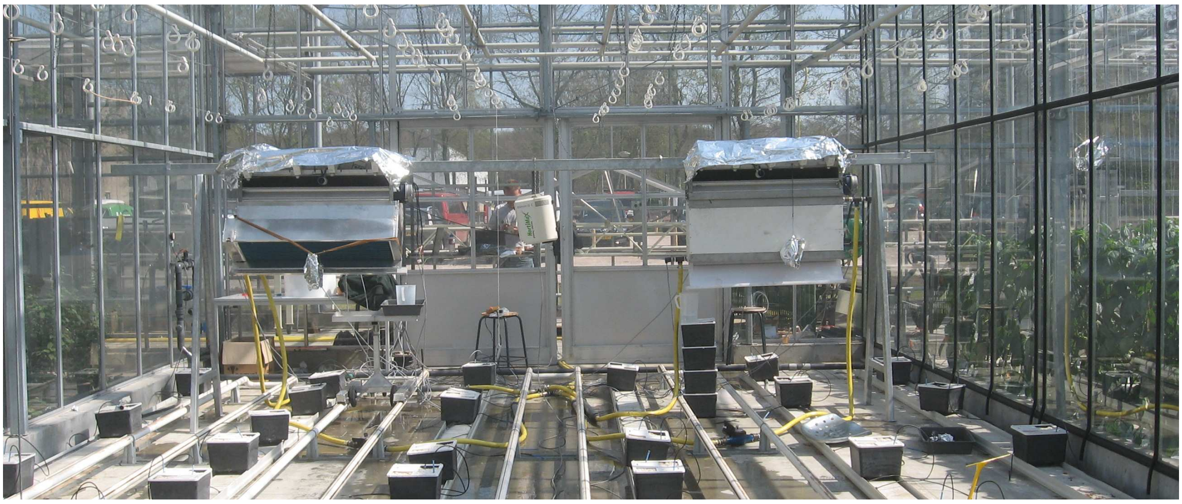
To place the performance of the OPAC106 in a broader light in section 5.2 is a comparison with the cooling units of the Energy Producing Greenhouses in the IDC (the coolers in the Sunergie greenhouse).

5.1 Comparison between OPAC106 and FiWiHEx heat exchangers

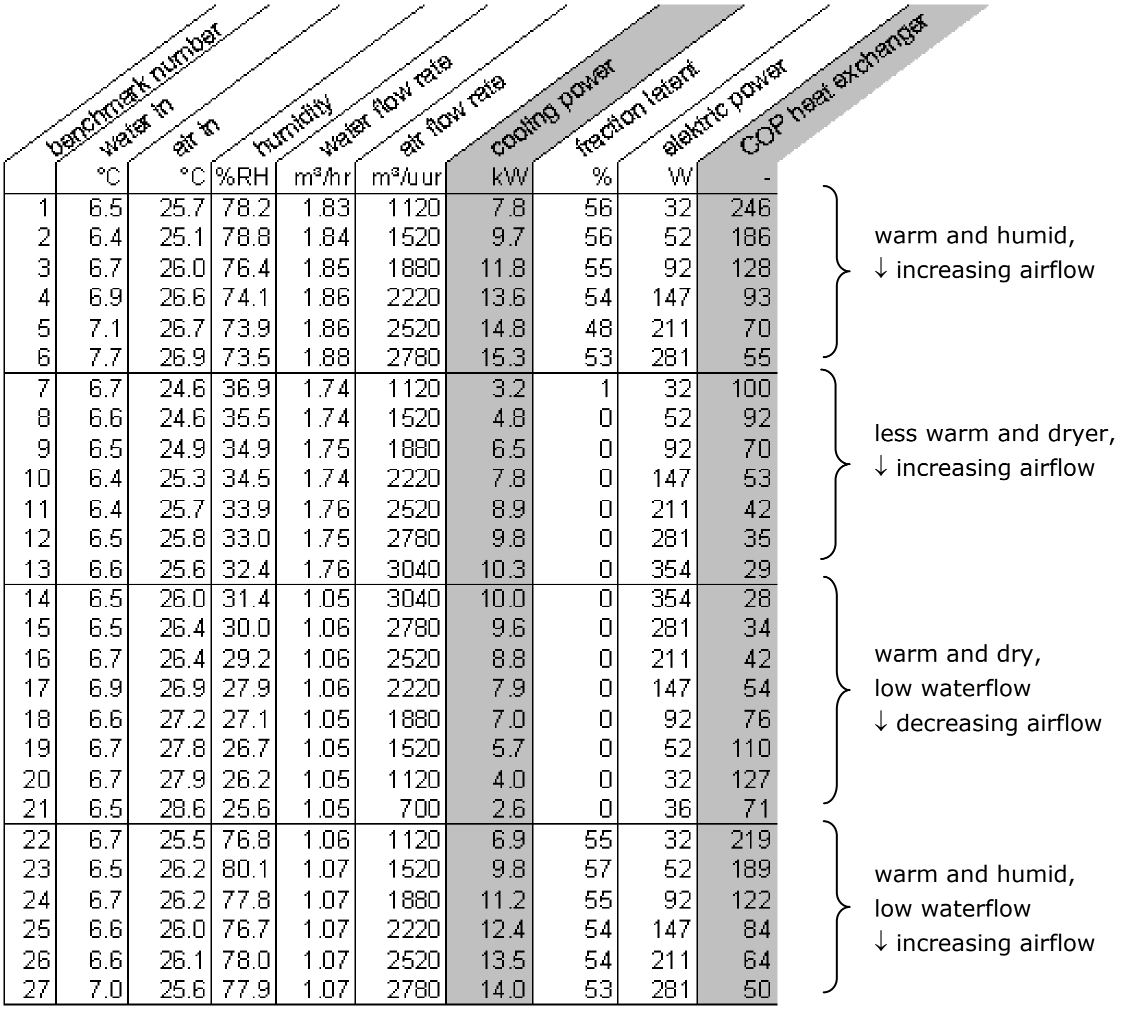
Simultaneously with the evaluation of the OPAC106 heat exchanger, tests were performed with a FiWiHEx heat exchanger. This heat exchanger has the same fan as the OPAC106 and the outer dimensions are quite the same. Since the measurements were simultaneously, the working conditions were almost identical (see Figure 10) which provided an equal set of 27 benchmark points for the FiWiHEx. These are shown in the table of Figure 11.
When comparing the results of the OPAC106 and the FiWiHEx, the cooling power of the OPAC106 appeared to be more than the FiWiHEx's in all 27 cases especially for the cases with the higher air flows. The main reason is that at equal (digital) control signal for the ventilator (both units in the experimental set up were controlled in parallel) the air flow through the OPAC106 heat exchanger was somewhat larger. Obviously then the cooling capacity is greater.

A final judgement on the efficiency of a heat exchanger, however, cannot be based solely a comparison of the actual heat exchange capacity, but also the power used by the cooling unit's fan should be taken into account. This means a comparison on the COP of the heat exchangers. An brief comparison of the COP data in Figure 4 and Figure 11 shows that the COP of the OPAC 106 is generally larger than the COP achieved by the FiWiHEx heat exchanger. However, an accurate comparison cannot be made because the 27 benchmark points are not exactly the same.

Therefore, again the heat exchanger simulation model is used, but parameterized for the performance of the FiWiHEx heat exchanger. Figure 12 shows the results of the simulation and the tests and indicates that also for the FiWiHEx heat exchanger the model provides a good match, especially under humid conditions.

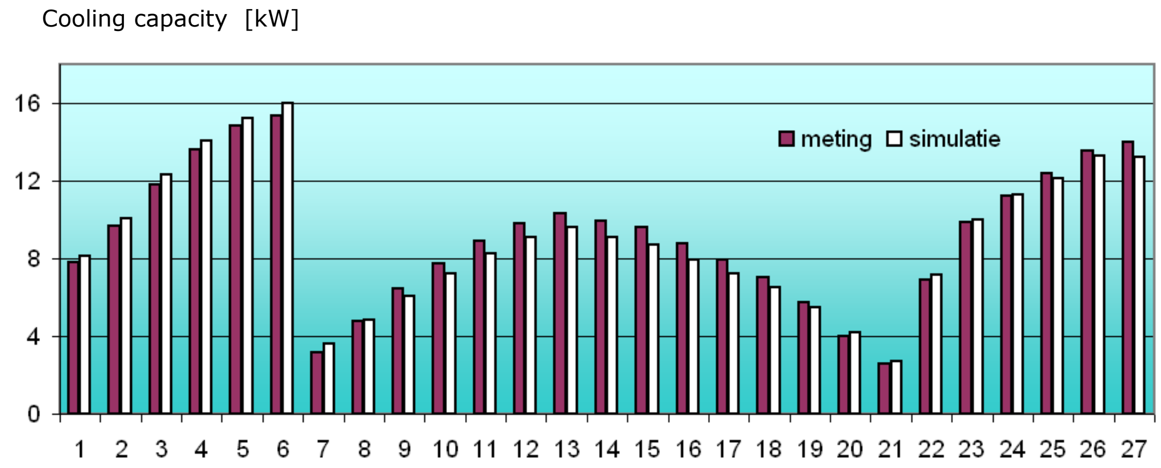


Figuur 10. Measuring system for the PTC + with the OPAC106 heat exchanger in parallel with the FiWiHEx heat exchanger



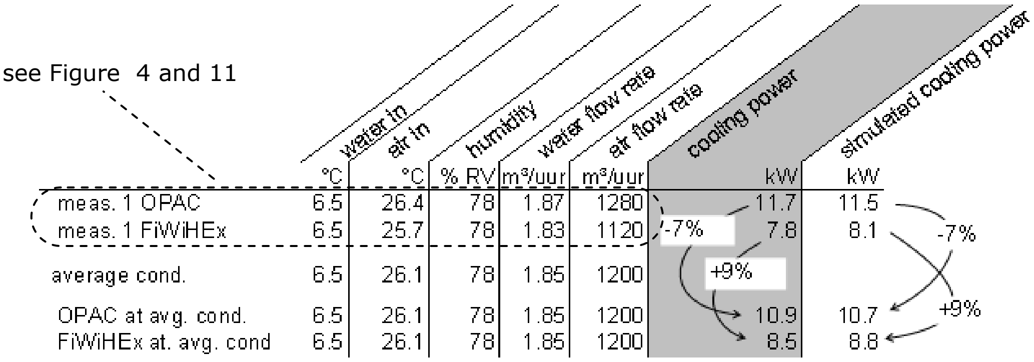
benchmark number	water in	air in	humidity	water flow rate	air flow rate	cooling power	fraction latent	elektric power	COP heat exchanger
	°C	°C	%RH	m³/hr	m³/uur	kW	%	W	-
1	6.5	25.7	78.2	1.83	1120	7.8	56	32	246
2	6.4	25.1	78.8	1.84	1520	9.7	56	52	186
3	6.7	26.0	76.4	1.85	1880	11.8	55	92	128
4	6.9	26.6	74.1	1.86	2220	13.6	54	147	93
5	7.1	26.7	73.9	1.86	2520	14.8	48	211	70
6	7.7	26.9	73.5	1.88	2780	15.3	53	281	55
7	6.7	24.6	36.9	1.74	1120	3.2	1	32	100
8	6.6	24.6	35.5	1.74	1520	4.8	0	52	92
9	6.5	24.9	34.9	1.75	1880	6.5	0	92	70
10	6.4	25.3	34.5	1.74	2220	7.8	0	147	53
11	6.4	25.7	33.9	1.76	2520	8.9	0	211	42
12	6.5	25.8	33.0	1.75	2780	9.8	0	281	35
13	6.6	25.6	32.4	1.76	3040	10.3	0	354	29
14	6.5	26.0	31.4	1.05	3040	10.0	0	354	28
15	6.5	26.4	30.0	1.06	2780	9.6	0	281	34
16	6.7	26.4	29.2	1.06	2520	8.8	0	211	42
17	6.9	26.9	27.9	1.06	2220	7.9	0	147	54
18	6.6	27.2	27.1	1.05	1880	7.0	0	92	76
19	6.7	27.8	26.7	1.05	1520	5.7	0	52	110
20	6.7	27.9	26.2	1.05	1120	4.0	0	32	127
21	6.5	28.6	25.6	1.05	700	2.6	0	36	71
22	6.7	25.5	76.8	1.06	1120	6.9	55	32	219
23	6.5	26.2	80.1	1.07	1520	9.8	57	52	189
24	6.7	26.2	77.8	1.07	1880	11.2	55	92	122
25	6.6	26.0	76.7	1.07	2220	12.4	54	147	84
26	6.6	26.1	78.0	1.07	2520	13.5	54	211	64
27	7.0	25.6	77.9	1.07	2780	14.0	53	281	50

Figuur 11. The 27 benchmark points of the FiWiHEx heat exchanger measured in parallel to measurements of the OPAC106 heat exchanger.



Figuur 12. Comparison of measurements and simulation of the FiWiHEx heat exchanger
Meting = measurement, simulatie = simulation

Now that the behavior of both heat exchangers can be described with a good explanatory model, for each of the 27 benchmark points the average working condition can be determined. Then the model can be used to determine how much the measurements would change upwards or downwards if the working conditions had been exactly equal to the average working condition. The procedure is explained on the basis of data from the first benchmark point.



see Figure 4 and 11

	water in	air in	humidity	water flow rate	air flow rate	cooling power	simulated cooling power
	°C	°C	% RV	m³/uur	m³/uur	kW	kW
meas. 1 OPAC	6.5	26.4	78	1.87	1280	11.7	11.5
meas. 1 FiWiHEx	6.5	25.7	78	1.83	1120	7.8	8.1
average cond.	6.5	26.1	78	1.85	1200		
OPAC at avg. cond.	6.5	26.1	78	1.85	1200	10.9	10.7
FiWiHEx at. avg. cond	6.5	26.1	78	1.85	1200	8.5	8.8

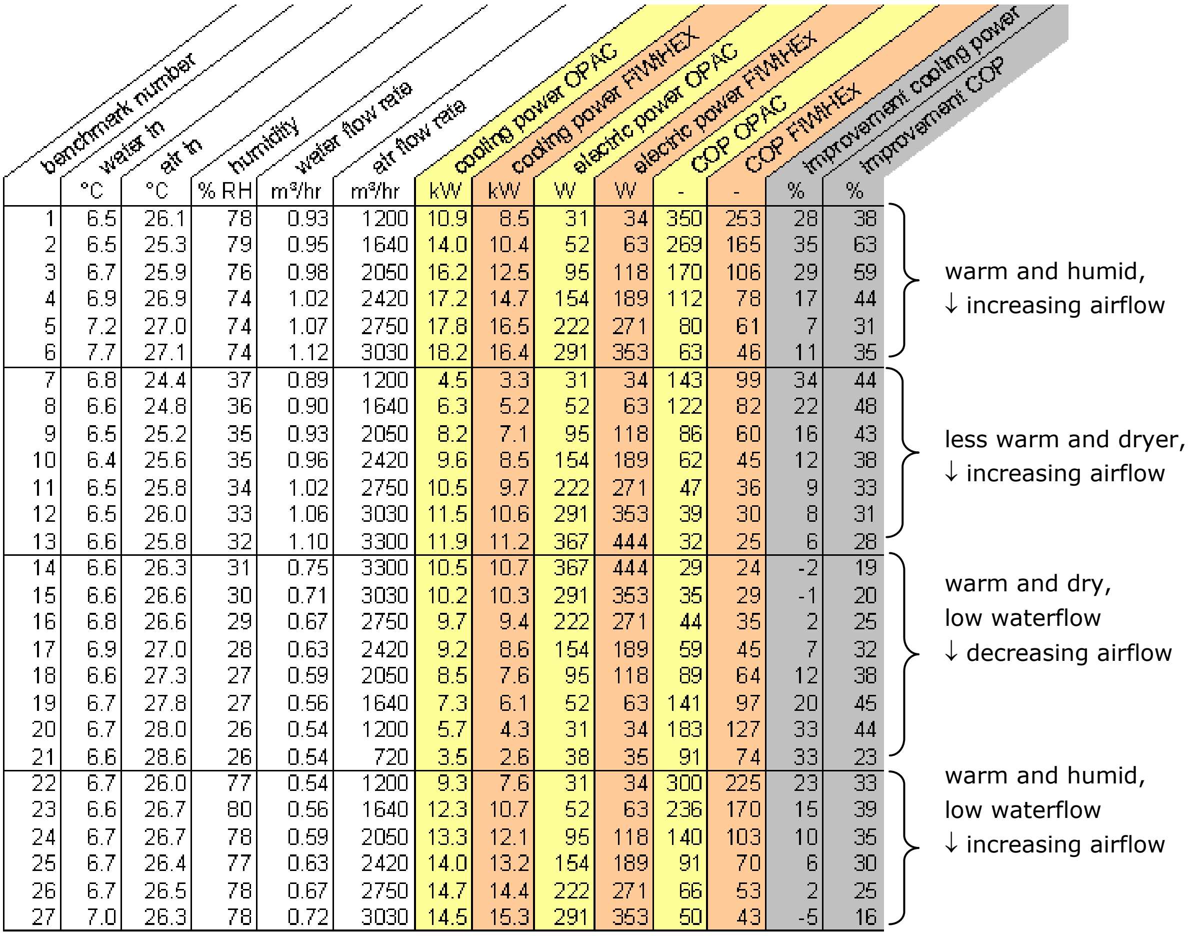
Figuur 13. Explanation of the procedure whereby the simulation model is used to the align the benchmark points. The percentage effect in the simulation is applied on the readings

The biggest difference between the operating conditions at the first benchmark point is in the air flow rate through the units (this is also the largest difference in all benchmark points). The other conditions differed only marginally.

When operating conditions based on the measurement data are equalized, less air goes through the OPAC106 and more air through the FiWiHEx heat exchanger. The simulation model calculates that under these circumstances the OPAC106 would deliver 7% less cooling capacity and the FiWiHEx would have cooled with 9% more power. A comparison between the OPAC106 FiWiHEx and under similar circumstances would therefore imply that the measured cooling capacity for OPAC106 7% should be reduced (and so would become 10.9 kW) and FiWiHEx increased by 9% (and hence would give 8.5 kW).

The electricity use for the OPAC106 heat exchanger at an air flow rate of 1200 m³/hr is 31 W and for 1200 m³/hr the FiWiHEx heat exchanger uses 39 W power.

The following table shows the results of the comparisons after all benchmark points were adjusted in a similar way as described above.



benchmark number	water in	air in	humidity	water flow rate	air flow rate	cooling power OPAC	cooling power FiWiHEx	electric power OPAC	electric power FiWiHEx	COP OPAC	COP FiWiHEx	improvement cooling power	improvement COP
	°C	°C	% RH	m³/hr	m³/hr	kW	kW	W	W	-	-	%	%
1	6.5	26.1	78	0.93	1200	10.9	8.5	31	34	350	253	28	38
2	6.5	25.3	79	0.95	1640	14.0	10.4	52	63	269	165	35	63
3	6.7	25.9	76	0.98	2050	16.2	12.5	95	118	170	106	29	59
4	6.9	26.9	74	1.02	2420	17.2	14.7	154	189	112	78	17	44
5	7.2	27.0	74	1.07	2750	17.8	16.5	222	271	80	61	7	31
6	7.7	27.1	74	1.12	3030	18.2	16.4	291	353	63	46	11	35
7	6.8	24.4	37	0.89	1200	4.5	3.3	31	34	143	99	34	44
8	6.6	24.8	36	0.90	1640	6.3	5.2	52	63	122	82	22	48
9	6.5	25.2	35	0.93	2050	8.2	7.1	95	118	86	60	16	43
10	6.4	25.6	35	0.96	2420	9.6	8.5	154	189	62	45	12	38
11	6.5	25.8	34	1.02	2750	10.5	9.7	222	271	47	36	9	33
12	6.5	26.0	33	1.06	3030	11.5	10.6	291	353	39	30	8	31
13	6.6	25.8	32	1.10	3300	11.9	11.2	367	444	32	25	6	28
14	6.6	26.3	31	0.75	3300	10.5	10.7	367	444	29	24	-2	19
15	6.6	26.6	30	0.71	3030	10.2	10.3	291	353	35	29	-1	20
16	6.8	26.6	29	0.67	2750	9.7	9.4	222	271	44	35	2	25
17	6.9	27.0	28	0.63	2420	9.2	8.6	154	189	59	45	7	32
18	6.6	27.3	27	0.59	2050	8.5	7.6	95	118	89	64	12	38
19	6.7	27.8	27	0.56	1640	7.3	6.1	52	63	141	97	20	45
20	6.7	28.0	26	0.54	1200	5.7	4.3	31	34	183	127	33	44
21	6.6	28.6	26	0.54	720	3.5	2.6	38	35	91	74	33	23
22	6.7	26.0	77	0.54	1200	9.3	7.6	31	34	300	225	23	33
23	6.6	26.7	80	0.56	1640	12.3	10.7	52	63	236	170	15	39
24	6.7	26.7	78	0.59	2050	13.3	12.1	95	118	140	103	10	35
25	6.7	26.4	77	0.63	2420	14.0	13.2	154	189	91	70	6	30
26	6.7	26.5	78	0.67	2750	14.7	14.4	222	271	66	53	2	25
27	7.0	26.3	78	0.72	3030	14.5	15.3	291	353	50	43	-5	16

warm and humid,
↓ increasing airflow

less warm and dryer,
↓ increasing airflow

warm and dry,
low waterflow
↓ decreasing airflow

warm and humid,
low waterflow
↓ increasing airflow

Figuur 14. Comparison of the performance of the OPAC 106 heat exchanger with the FiWiHEx heat exchanger. In almost all cases, the OPAC106 provides a higher cooling capacity. The power consumption of the fan at a given air flow in the case of the OPAC 106 heat exchanger is always lower. Therefore, the COP of the heat exchanger OPAC106, (the cooling capacity per unit electric power) is higher in all cases.

In almost all cases, the OPAC106 heat exchanger provides a larger cooling capacity than the FiWiHEx heat exchanger. In terms of heat transfer efficiency, the difference is even bigger because of the electricity use of the OPAC106 heat exchanger for a given air flow rate is lower than when the fan moves

the same amount of air through the FiWiHEx heat exchanger. The COP for heat transfer is thereby significantly improved.
Because, with all things being equal, the OPAC106 heat exchanger for a specific cooling capacity needs to move less air the OPAC106 heat exchanger has typically a lower noise level than FiWiHEx heat exchanger. However, this effect was not numerically (using a decibel meter) demonstrated.

In the final stage of the simultaneous testings, also a brief observation of the water flow resistance was carried out. It appeared that the pressure head required for water circulation through the OPAC 106 heat exchanger was less than that of the FiWiHEx heat exchanger. Thus, an OPAC106 heat exchanger will use less electricity for pumping water than a FiWiHEx heat exchanger. The difference is around a 10% order of magnitude and in absolute terms about 1 kWh per square meter greenhouse per year.

5.2 Comparison between OPAC106 and cooling units in the ’Sunergy Greenhouse’

The Sunergy Greenhouse is a closed greenhouse at the Innovation and Demo Centre in Bleiswijk (the Netherlands). Over the past year and a half, this greenhouse was monitord intensively. In this greenhouse, 6 cooling units are mounted, each blowing a more or less similar amount of air as the maximum airflow through the OPAC106 heat exchanger. A picture of two of these cooling units is shown in Figure 15.

Figuur 15. Picture of two of the six air conditioners in the ‘Sunergy Greenhouse’. The left-side heat exchanger demonstrates the fan for air flow and the right one shows the heat exchanger surface on the suction side. The coolers are mounted at 6.5 meters height.

On the basis of measurements of the chillers in the Sunergy Greenhouse, the heat exchanger simulation model’s parameters were changed for these chillers so the performance can be compared in a uniform way. Two water flow rates were examined, but because the chillers in the Sunergy Greenhouse work at one air flow rate only, for both cases the airflow was 3000 m^3/hr.

Tabel 1. *The performance of the OPAC106 heat exchanger in comparison with the performance of the coolers of the Sunergy Grenhouse. In all cases the greenhouse temperature was at 28 °C and 85% RH and the cooling water temperature was 10 °C. The air flow in all cases 3000 m³/hr because the chillers only work at one air flow rate.*

	waterflow	Cool capacity	Electr. fan	COP
OPAC106	1.9 m³/hour	19.9 kW	280 W	70
SunergieKas		20.5 kW	450 W	45
OPAC106	0.8 m³/hour	12.8 kW	280 W	46
SunergieKas		13.1 kW	450 W	29

Based on the above table it can be concluded that the chillers in the Sunergy Greenhosue have a larger heat transfer, but a lower efficiency in terms of the quantity of electricity used per unit of cooling. At lower heat loads, the difference between the efficiency of OPAC106 and the Sunergy Greenhouse coolers increases because the fan of the Sunergy cooler cannot be modulated (the fan is either on or off). In practice, the OPAC106 heat exchanger at a lower power demand can, besides the reduction of water flow rate, in particular reduce the air flow rate.

The simulation shows that when the OPAC106 heat exchanger, like the cooler in the Sunergy Greenhouse, must provide 13.1 kW cooling power, one could choose for a water flow rate of e.g. 1 m³ per hour and an air flow rate of 2100 m³hr. In that case the fan would use only 100 watts of electricity so a COP of 130 would result. At the other hand the electricity consumption for pumping will increase, but much less than the savings of electricity for the fans.

6 Conclusions

At high load in a warm and humid greenhouse (28 °C and 85% RH), the OPAC106 heat exchanger, fed with cooling water of 10 °C at a water flow rate of 1.8 m^3/hr, realizes a cooling capacity of 20 kW per unit. This holds for an air flow rate of 3000 m^3/hr, with the fan using 280 W electric power. Then, this cooling unit is working at a COP of 70, which means that the unit gives 70 times as much cooling power than the electric power needed by the fan.

The stated 3000 m^3/hr is not the maximum air flow rate. The fan can drag almost 3600 m^3/hr through the heat exchanger, but this improves the cooling by only 10% while the electricity consumption nearly doubles.

Obviously, cooling capacity improves when lower cooling water temperatures are used or when the greenhouse air is warmer and/or more humid. Conversely, it has lower cooling capacity by warmer cooling water and cold greenhouse temperatures and lower humidity. Due to the sensitivity of the performance to the operating conditions, a simulation model was made that calculates the performance under any circumstances. With this model, also the performance of the heat exchanger in heating mode can be determined.

A comparison of the OPAC106 heat exchanger with other heat exchangers which may be considered more or less comparable alternatives (a similar build size and a comparable cooling capacity) shows the OPAC106 heat exchanger to outperform the alternatives. Especially in terms of heat transfer per unit electrical energy supplied, the OPAC106 performs better.

Since the OPAC106 heat exchanger in cooling mode, realizes a greater heat transfer (also in situations without condensation) it can be stated that the heat transfer in the heating mode will also be greater.

With the fact that electricity consumption of fans in semi-closed greenhouses is about 15 kWh per m^2 (data from Sunergy Greenhouse)[1], it can be calculated that the effect of the improved heat transfer is a 5 kWh saving of electricity per square meter per year. If the heat exchanger is used also for heating, the OPAC 106 heat exchanger saves about 3 kWh per m^2 per year on the electricity consumption of the ventilators when used for heating. The savings are smaller because the average load of the heat exchanger while heating is smaller then when cooling and because the average temperature difference between water and air for heating is usually greater.

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[1] Performance of demo-greenhouses at the Innovation and Demonstration Centre, English summary of the research carried out at the Innovation and Demonstration Centre