TRNSYS-TYPE 144

Assessment of an indoor or outdoor swimming pool

TRANSSOLAR
Energietechnik GmbH
Strategies for energy efficient design and thermal comfort in buildings

Thomas Auer

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Contents

Symbols

Latin Symbols

A	Area
a	Thermal diffusivity
c_p	Specific heat
D	Diffusion coefficient
dE	Change of internal energy (form start of simulation till end of simulation)
$E_{Glob,H}$	Total solar radiation on a horizontal surface
H	Enthalpy
Δh_{Evap}	Enthalpy of evaporation
m	Mass
$\dot{m}$	Mass flow rate
p	Pressure
$\dot{Q}$	Rate of heat transfer
T	Absolute temperature
t	Time
c_p	Specific heat
V	Volume

Greek Symbols

a	Heat transfer coefficient
a_{Evap}	Evaporation coefficient
b	Mass transfer coefficient
d	Thickness
e	Total evaporation coefficient
e^*	Emissivity
j	Relative humidity
l	Thermal conductivity
r	Density
s	Stefan-Boltzmann constant
J	Temperature

Subscripts

Amb	Ambient
P	Pool
Cov	Cover
$Cond$	Conductivity
St	Steam
Fr	Fresh water
$total$	Total
In	Input
Con	Convection
$Pipe$	Piping
Air	Air
Out	Output
Rad	Long-wave radiation
Sat	Saturation
Sol	Solar
$Evap$	Evaporation
W	Water
aux	auxiliary
0	Initial value

1 Basic Physical Principles

It is assumed that the water in the swimming pool is ideally mixed so that the first law of thermodynamics can be expressed as follows:

$$\frac{dH}{dt} = \sum\left(\dot{Q}_{In} - \dot{Q}_{Out}\right) \quad (1)$$

It can also be assumed that a liquid is incompressible and that density and thermal conductivity are constants. Equation (1) can then be expressed as follows:

$$\rho_W \cdot c_{p,w} \cdot V_P \cdot \frac{dT}{dt} = \sum\left(\dot{Q}_{In} - \dot{Q}_{Out}\right) \quad (2)$$

When drawing up the model, it was further assumed that there is a constant amount of water in the pool.

The following figure shows a schematic view of all heat flow rates:

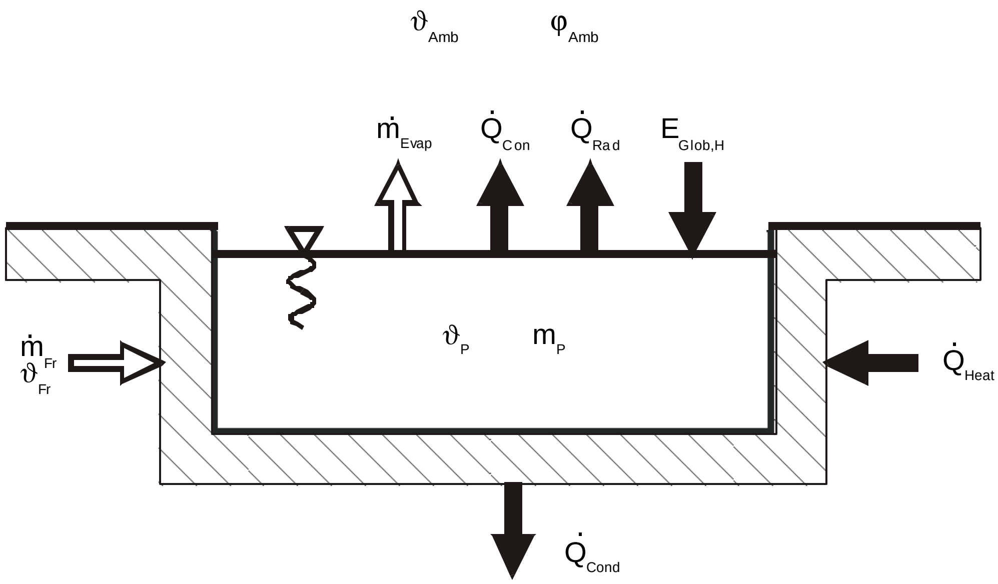

Figure 1: Heat and Mass Flow Rates of a Pool in Exchange with the Ambient

The heat exchange with the surroundings includes the following:

- Heat flow rate by evaporation
- Heat flow rate by convection
- Heat flow rate by short-wave radiation
- Heat flow rate by long-wave radiation
- Heat loss by fresh water supply
- Heat flow rate from heating
- Thermal conduction to the ground

The heat flow rate to the ground is negligible for this assessment. Indoor pools are normally surrounded by engineering rooms in the basement with ambient temperatures generally higher than 30°C so that the heat flow rate is virtually zero. For outdoor pools this aspect may be ignored, because, on the one hand it has only a minor influence on the overall energy assessment (<1 %) and on the other, because it cannot be calculated accurately ($\dot{Q}_{Cond} = f$ (*thermal insulation*, *composition of the ground*).

In the following section each heat flow rate is calculated in detail.

1.1 Calculation of Heat Flow Rate by Evaporation

The heat loss by evaporation can be calculated on the basis of the evaporated mass flow rate with the following expression:

$$\dot{Q}_{Evap} = \dot{m}_{Evap} \cdot \Delta h_{Evap} \quad (3)$$

The evaporated mass flow rate can be determined with a formula for the calculation of a motive force. The driving force is the difference in pressure of the water steam between the water surface and the surroundings, and it is assumed that a layer directly above the water surface, at the pool water temperature, has a relative humidity of 100 %. For an indoor pool the evaporated mass flow rate can be calculated with the following equation:

$$\dot{m}_{Evap} = e \cdot A_{total} \cdot \left(p_{Sat}(J_P) - p_{St}(J_{Amb}) \right) \quad (4)$$

The steam pressure in ambient conditions can be calculated using the relative humidity determined by the following formula:

$$p_{St} = j_{Amb} \cdot p_{Sat}(J_{Amb}) \quad (5)$$

The total evaporation coefficient e for a choppy water surface is taken from the VDI[1)] Guideline 2089 [2]. Calculations for a pool without swimmers are based on measurements of an indoor pool at Schalmtal carried out by Biasin. From these measurements, Biasin concluded and documented the theoretical principles for the calculation of the total evaporation coefficient [1].

The evaporation relation for an outdoor pool is based on an empirical formula whereby the total evaporation coefficient and the evaporation enthalpy are combined so that the heat flow rate by evaporation can be calculated with the following equation:

$$\dot{Q}_{Evap} = A_{total} \cdot a_{Evap} \cdot \left(p_{Sat}(J_P) - p_{St}(J_{Amb}) \right) \quad (6)$$

According to D. Richter [4] the modified evaporation coefficient can be calculated as follows:

$$a_{Evap} = 50.58 + 66.9 \cdot w_{Amb}^{0.5} \quad (7)$$

This equation gare goot results for reproducing the change of temperature for the outdoor pool at Leonberg (based on calculations carried out by the Institut für Thermodynamik und Wärmetechnik der Universität Stuttgart (Institute for Thermodynamics and Heat Technology at Stuttgart University/Germany) [5].

1.2 Calculation of Heat Flow Rate by Convection

The heat flow rate by convection can be calculated on the basis of Newton's formula:

$$\dot{Q}_{Con} = a \cdot A_{total} \cdot \left(J_P - J_{Amb}\right) \tag{8}$$

According to Biasin's measurements, Lewis's formula for mass and heat transfer can be used for indoor pools so that the relation between the heat and mass transfer coefficients can be determined with the following equation:

$$\frac{a}{b} = c_{pl} \cdot p_l \cdot \left(\frac{a}{St}\right) \tag{9}$$

The heat transfer coefficient for an outdoor pool can be calculated on the basis of the following formula, found by J. T. Czarnecki [6]:

$$a = 3.1 + 4.1 \cdot w_{Amb} \tag{10}$$

1.3 Calculation of Heat Flow Rate by Long-Wave Radiation

The heat transfer rate by long-wave radiation exchange with the walls (indoor pools) or the sky (outdoor pools) can be calculated on the basis of the Stefan-Boltzmann law. For the indoor pool it can be assumed that the pool is completely enclosed, and for the outdoor pool we assume that the surface area of the "sky" is large compared to that of the pool. Thus, in both cases, the heat flow rate by long-wave radiation is reduced to the heat flow rate to a full radiator. Therefore the relation can be expressed by the following formula:

$$\dot{Q}_{Rad} = A_{total} \cdot \varepsilon_w^* \cdot \sigma \cdot \left(T_P^4 - T_X^4\right) \tag{11}$$

Where *X* can stand for *Wall* as well as for *Sky*.

The constants have the following values:

$$e_W^* = 0.9$$

$$s = 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$$

1.4 Calculation of Heat Loss by Fresh Water Supply

The heat loss by fresh water supply can be calculated using the first law of thermodynamics under the assumption of an incompressible liquid as follows:

$$\dot{Q}_{Fr} = m_{Fr} \cdot c_{p,W} \cdot \left(J_P - J_{Fr} \right) \tag{12}$$

1.5 Calculation of Heat Flow Rate by Short-Wave Thermal Gain

The short-wave thermal gain from total solar radiation on a horizontal surface for an outdoor pool can be calculated as follows:

$$\dot{Q}_{Sol} = e^{*}_{w} \cdot A_{total} \cdot E_{Glob,H} \tag{13}$$

The short-wave thermal gain for an indoor pool have to be determined differently. When this TYPE is combined with TYPE 56, the solar gain striking at the pool surface can be determined and used.

1.6 Calculation of Heat Flow Transfer of the Auxiliary Heating

Analogous to the heat loss by fresh water supply the heat flow rate of the auxiliary heating can be calculated with the following formula:

$$\dot{\mathrm{Q}}_{\mathrm{In}} = \mathrm{m}_{\mathrm{In}} \cdot \mathrm{c}_{\mathrm{p,W}} \cdot \left(\vartheta_{\mathrm{P}} - \vartheta_{\mathrm{In}} \right) \tag{14}$$

1.7 Calculation of Stored Energy

For a complete energy balance, the temperature difference between initial and final conditions must be considered. The stored energy can be calculated as follows:

$$\mathrm{dE} = \mathrm{m}_{\mathrm{P}} \cdot \mathrm{c}_{\mathrm{P,w}} \cdot \left(\vartheta_{\mathrm{P,0}} - \vartheta_{\mathrm{P}} \right) \tag{15}$$

1.8 Heat Loss of a Covered Pool

If the water surface of a pool is covered, the heat loss is reduced, mainly because evaporation is prevented by the cover. Figure 2 shows a schematic view of all heat flow rates.

The heat flow rate for a covered water surface is reduced to a convective share, a short-wave and a long-wave heat flow rate resulting in a given temperature on top of the cover. We can assume that a stationary temperature profile is formed at any time, because of the small mass of the cover. Therefore the thermal slow rate balance of the cover can be reduced to the following formula:

$$0 = \dot{Q}_{Con} + \dot{Q}_{Rad} + \dot{Q}_{cond} - \dot{Q}_{Sol} \tag{16}$$

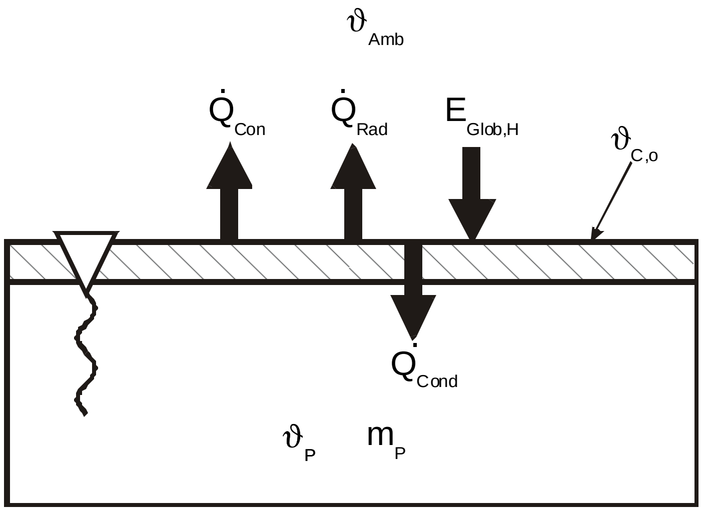

Figure 2: Heat Flow Rates of a Pool Cover

With regard to the temperature on top of the cover each heat flow rate can be expressed as follows:

$$\dot{Q}_{Con} = a \cdot A_{Cov} \cdot \left(J_{C,0} - J_{Amb} \right) \tag{17}$$

$$\dot{Q}_{Rad} = A_{cov} \cdot e^{*}_{Cov} \cdot s \cdot \left(T^{A}_{C,0} - T^{A}_{X} \right) \tag{18}$$

$$\dot{Q}_{Cond} = \frac{\lambda_{Cov}}{\delta_{Cov}} \cdot A_{Cov} \cdot \left(\vartheta_{C,0} - \vartheta_{P} \right) \tag{19}$$

$$\dot{Q}_{Sol} = A_{Cov} \cdot e^{*}_{Cov} \cdot E_{glob,H} \tag{20}$$

The heat transfer coefficient required for the calculation of the heat flow rate by convection can be calculated with equation (10). For the heat flow rates by short-wave and long-wave radiation it was assumed that the Kirchhoff law is valid, which states that absorption values equal emission values.

2 Description of TYPE 144 for the Calculation of an indoor or outdoor pool

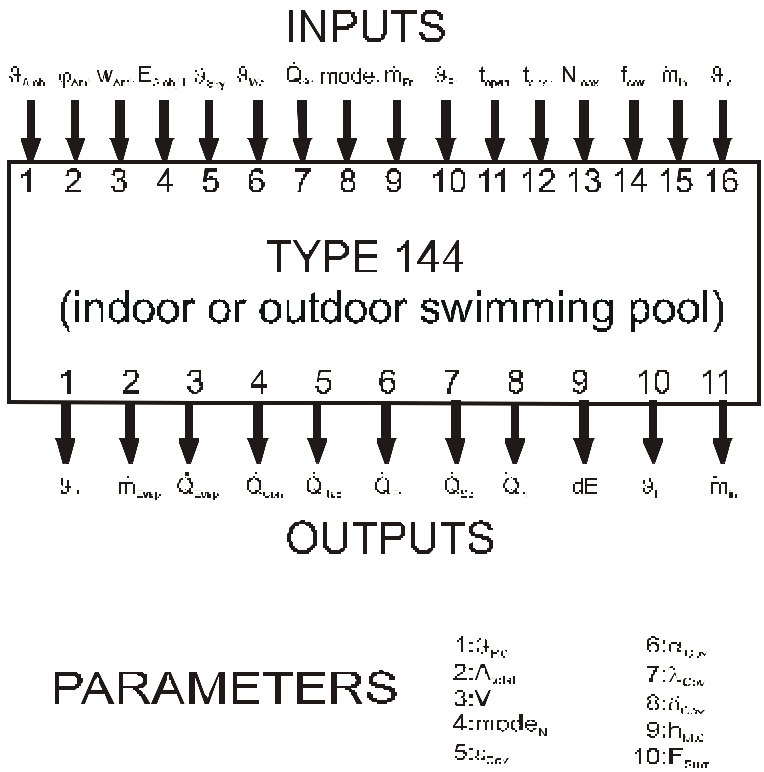

Figure 3: Parameter, Input and Output Data of Type 144

2.1 Description of Parameters

The following parameters can be used for the calculation of indoor or outdoor pools:

Parameter No	Symbol	Description	Unit
1	$J_{P,0}$	Initial Temperature of Pool Water	°C
2	A_{total}	Total Surface Area of the Pool	m²
3	V	Pool Water Volume	m³
4	$mode_N$	Distinction between indoor and outdoor pool	-
5	e_{Cov}	Emissivity of the Cover	-
6	a_{Cov}	Absorption coefficient of the Cover	-
7	l_{Cov}	Thermal Conductivity of the Cover	kJ/(hm·k)
8	d_{Cov}	Thickness of the Cover	m
9	$h_{M,0}$	Height of Wind Velocity Measurements	m
10	F_{Surr}	Factor of Surroundings	-

Table 1: List of Parameters

1. Initial Temperature of Pool Water ($J_{P,0}$)
Pool water temperature at the beginning of the simulation.

2. Total Surface Area of the Pool (A_{total})
Surface area of the pool including the overflow-pipe system.

3. Pool water volume (V)
Water content of the pool.

4. Distinction between indoor and outdoor pools ($mode_N$)
The parameter $mode_N$ shows the distinction between the calculation for an indoor and an outdoor pool:

$mode_N = 0 \Rightarrow$ indoor pool

$mode_N > 1 \Rightarrow$ outdoor pool

5. Emissivity of the Cover (e_{Cov})

6. Absorption coefficient of cover (a_{Cov})

7. Thermal Conductivity of the Cover (l_{Cov})

8. Thickness of the Cover (d_{Cov})

9. Height of Wind Velocity Measurements ($h_{M,0}$)
(see Parameter 10)

10. Factor of Surroundings (F_{Surr})
The heat loss of an outdoor pool (by evaporation and convection) depends largely on the wind velocity (see "Basic Physical Principles"). The relations used in the calculation are based on wind velocity measured at a height of 3 m. As this is not the height at which wind velocity is normally measured for weather data, a correction factor needs to be introduced. The correction factor depends on the surroundings. Figure 5 shows the graphs for different wind velocities under the influence of the correction factor and depending on the factor of surroundings (F_{Surr}).

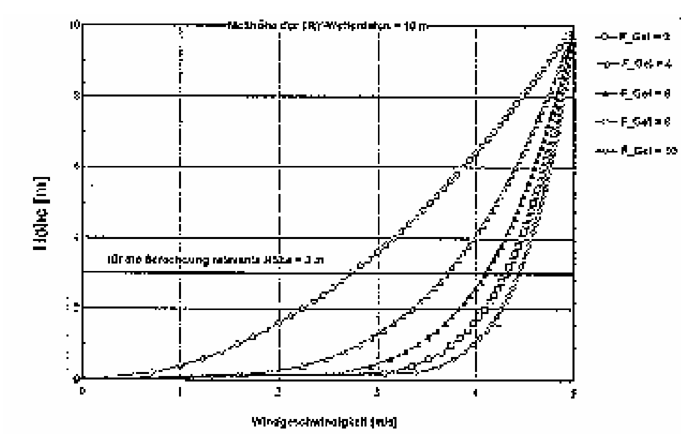

Figure 4: Wind Velocity Depending on the Height and on the Factor of Surroundings (F_{Surr}) on the Basis of a Wind Velocity of 5 m/s Measured at a Height of 10 m.

The calculation is based on the following equation:

$$\frac{w}{w_0} = \left(\frac{z}{z_0}\right)^{\frac{1}{F_{Surr}}} \qquad (21)$$

The following guideline values can be assumed for the factor of surroundings:

Area with high building density	2
Town with moderate building density	2..4
Area with forests or hills	3..6
Free plains	6..8
Free water surfaces	8..10

Table 2: Guideline Values for Factor of Surroundings

2.2 Description of Inputs

The following input values can be used for calculating the thermal assessment of an indoor or outdoor pool:

Input No	Symbol	Description	Unit
1	J_{Amb}	Ambient Air Temperature	°C
2	j_{Amb}	Relative Humidity of Ambient Air	%
3	W_{Amb}	Wind velocity of Ambient Air	m/s
4	$E_{Glob,H}$	Total Solar Radiation on a Horizontal Surface	kJ/hm²
5	J_{Sky}	Temperature of the "Sky"	°C
6	J_{Wall}	Temperature of Enclosing Surfaces (Walls)	°C
7	$\dot{Q}_{Sol}$	Short-Wave Radiation Gain	kJ/h
8	$mode_1$	Expressing the Activity of the Water Surface	-
9	$\dot{m}_{Fr}$	Mass Flow Rate of Fresh Water Supply	kg/h
10	J_{Fr}	Temperature of Fresh Water	°C
11	t_{open}	Swimming Pool Opening Time	h
12	t_{close}	Swimming Pool Closing Time	h
13	$N_{\max}$	Maximum Pool Occupancy on a Given Day	-
14	f_{Cov}	Relative Covering of Water Surface	-
15	$\dot{m}_{In}$	Mass Flow Rate of Supply from Heating	Kg/h
16	J_{In}	Temperature of Supply	°C

Table 3: List of Inputs

1. Ambient Air Temperature (J_{Amb})

When calculating an outdoor pool, use the ambient air temperature outdoors, and for an indoor pool use the ambient air temperature indoors.

2. Relative Humidity of Ambient Air (j_{Amb})

Use the relative humidity of the outdoor air (outdoor pools) and of the indoor air (indoor pools).

3. Wind velocity of Ambient Air (w_{Amb})

This parameter is only relevant for the calculation of outdoor pools. Since the wind velocity is a function of the height above ground and also depends closely on the microclimate, two additional parameters were introduced for a more accurate calculation (see table 1: List of parameters).

4. Total Solar Radiation on a Horizontal Surface ($E_{Glob,H}$)

The total solar radiation on a horizontal surface is required to calculate the short-wave radiation gain of an outdoor pool (not used for an indoor pool).

5. Temperature of the "Sky" (J_{Sky})

To calculate the heat flow rate by long-wave radiation, use a fictitious sky temperature, which can be calculated with TYPE 69 (for handling see User's Manual).

6. Temperature of enclosing surfaces (J_{Wall})

The average temperature of the enclosing surfaces is required to calculate the heat flow rate by long-wave radiation of an indoor pool. When this TYPE is combined with TYPE 56, the average internal surface temperatures has to be used (See NTYPE 24 of TYPE 56).

7. Short-wave radiation gain ($\dot{Q}_{Sol}$)

Input 7 is only used for the assessment of indoor pools. The short-wave radiation gain is that solar gain which is directed through the window glazing to the water surface (when this TYPE is combined with TYPE 56, this short-wave radiation gain in relation to the surface area equals NTYPE 21 of TYPE 56).

8. Expressing the calmness of the water surface ($mode_1$)

Since the activity of the water surface greatly affects the rate of evaporation and convection, it is taken into account in the form of a factor, which is very similar to the VDI[1)] values. The factors stand for the following conditions:

$mode_1$ = 0 ⇒ calm water surface

$mode_1$ = 1 ⇒ slightly choppy water surface (private pool)

$mode_1$ = 2 ⇒ slightly choppy water surface (public indoor pool, normal pool occupancy)

$mode_1$ = 3 ⇒ moderately choppy water surface (fun pool)

$mode_1$ = 4 ⇒ very choppy water surface (artificially induced waves)

$mode_1$ = -1 ⇒ function of pool occupancy

The function of pool occupancy ($mode_1$ = -1) produces a parabolic graph with the maximum value in the middle, for which inputs 11, 12 and 14 are required. Figure 5 shows the graph of the function of pool occupancy for different maximum values of pool occupancy.

9. Mass Flow Rate of Fresh Water Supply ($\dot{m}_{Fr}$)

Input 9 only expresses the water exchange required for reasons of hygieny (or the water exchange resulting from filtered water coming back from the filter). Water loss due to evaporation is automatically compensated internally.

10. Temperature of Fresh Water (J_{Fr})

Temperature of the water supply mass flow rate of Input 9. The supply of water, as compensation for water loss due to evaporation, is included in the calculation at the same temperature.

11. Swimming Pool Opening Time (t_{open})

The swimming pool opening time is required for the function of pool occupancy (see Input 8).

12. Swimming Pool Closing Time (t_{close})

(see Input 11 and 8)

13. Maximum Pool Occupancy on a Given Day ($N_{\max}$)

Input 13 is also required for the calculation of the function of pool occupancy (Input 8). The maximum pool occupancy in the pool on a given day has to be entered. If, for example, a pool with a surface of 100 m^2 is assigned a maximum number of swimmers of 100, the function of pool occupancy reaches a factor of 4 as its maximum value (see Figure 5).

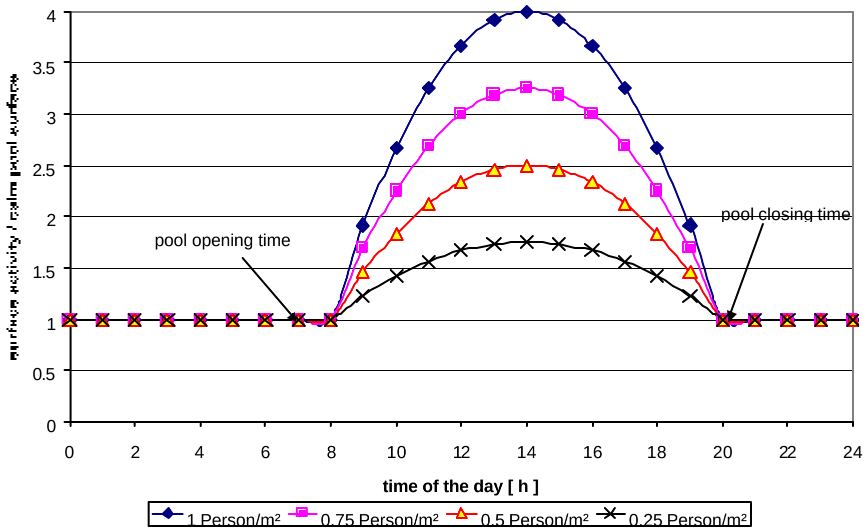

Figure 5: Change of the Function of Pool Occupancy over the Course of the Day for Different Maximum Values of Pool Occupancy. Opening time 8 a.m., closing time 8 p.m.

14. Relative Covering of Water Surface (f_{Cov})

Percentage of water surface covered ($f_{Cov} = 0\ldots1$).

15. Mass Flow Rate of Supply from Heating ($\dot{m}_{In}$)

Mass flow rate of the supply coming from the heating circuit.

16. Temperature of Supply (J_{In})

Temperature of the supply coming from the heating circuit.

2.3 Description of Outputs

For the calculation of an indoor or outdoor pool the following output values can be used:

Output No	Symbol	Description	Unit
1	J_P	Temperature of Pool Water	°C
2	$\dot{m}_{Evap}$	Mass Flow Rate of Evaporation	kg/h
3	$\dot{Q}_{Evap}$	Heat Flow Rate by Evaporation	kJ/h
4	$\dot{Q}_{Con}$	Heat Flow Rate by Convection	kJ/h
5	$\dot{Q}_{Rad}$	Heat Flow Rate by Long-Wave Radiation	kJ/h
6	$\dot{Q}_{Fr}$	Heat Loss by Fresh Water Supply	kJ/h
7	$\dot{Q}_{Sol}$	Short-Wave Radiation Gain	kJ/h
8	$\dot{Q}_{In}$	Auxiliary Heat Flow Rate from Heating	kJ/h
9	dE	Internal energy change from the start of the simulation	kJ
10	J_P	Temperature of Pool Water	°C
11	$\dot{m}_{In}$	Mass Flow Rate from Heating Circuit	kg/h

Table 4: List of Outputs

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