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Evaporation from svimming pools

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Introduction

In order to determine the economically optimum quantity of air and components in a ventilation system it is necessary to know the evaporation rate as a function of the temperature of the room and the water, the relative humidity and the level of activity. In the literature several methods are given for calculating this evaporation. However these produce completely different results, so full-scale measurements were needed in order to provide a better model for evaporation from swimming pools.

In this paper full-scale measurements are adapted to a semi-empirical model. This model is based on conventional theory of mass and heat transfer adapted to suit the practical conditions in indoor swimming pools.

The first part of the paper presents the basis of the semi-empirical model. The measurements are stated in the second part.

Theoretical Evaluation

Transfer of sensible heat from homogeneously mixed moist air with temperature t_∞ to a unit liquid surface with temperature t_w can be expressed by using a mean heat transfer coefficient α in the following way, (see Figure 1):

$$q = \alpha(T_\infty - T_w) \quad [\text{w/m}^2] \qquad (1)$$

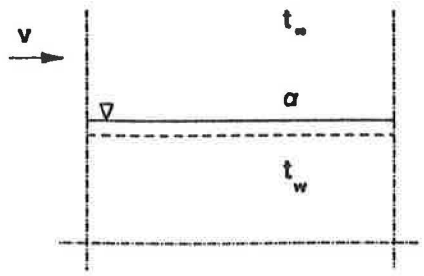


Fig. 1. Analogy heat and mass transfer

NOMENCLATURE

q =	sensible heat, [W/m^2]
α =	heat transfer coefficient, [W/m^2 K]
T =	temperature, [K]
t =	temperature, [°C]
σ =	evaporation coefficient, [kg water/(s m^2 (kg water/kg dry air)) = kg dry air/s m^2]
X =	water vapour content, [kg water/kg dry air] or [g water/kg dry air]
$\dot{m}$ =	exchange of vapour, [kg/s m^2] or [g/h m^2]
r =	latent heat of evaporation (Ws/kg)
c_p =	specific heat, [Ws/kg K], for moist air at $\frac{T_\infty - T_w}{2}$
h_D =	mass transfer coefficient, [m/s]
ρ =	density of moist air, [kg/m^3] at $\frac{T_\infty - T_w}{2}$
a =	thermal diffusion of moist air, [m^2/s]
p =	air pressure, [bar]
ϕ =	relative humidity, [%] or [0-1]
u =	density velocity, [m/s]
w =	forced velocity, [m/s]
x =	thickness of the boundary layer, [m]
g =	acceleration of gravity, [m/s^2]

SUFFIXES

∞ =	value in the homogeneous overlaying air
w =	values at the water surface
n =	free convection
t =	forced convection
c =	general convection
s =	value for saturated air
e =	value for exhaust air
s =	value for supply air
o =	value for outdoor air

Exchange of vapour between the liquid surface and the room air is expressed as:

$$\dot{m} = \sigma(X_w - X_\infty) \quad [\text{kg/s m}^2] \tag{2}$$

When the latent heat that is taken from the surface by evaporation is balanced by the sensible heat coming from the overlaying air, we can set up an adiabatic equation:

$$q = \dot{m} \cdot r \quad [\text{W/m}^2] \tag{3}$$

The expression of heat balance for an adiabatic evaporation from a liquid surface gives the Lewis relation:

$$Le = \frac{r \cdot (X_w - X_\infty)}{C_p(t_\infty - t_w)} = \frac{\alpha}{\sigma C_p} = \frac{\alpha}{h_D \rho C_p} \tag{4}$$

According to T. Kusuda [1] the Lewis number for free convection can be given as:

$$Le_n = \left(\frac{a}{D}\right)^{0.48} \tag{5}$$

and for forced convection as

$$Le_f = \left(\frac{a}{D}\right)^{\frac{2}{3}} \tag{6}$$

For indoor swimming pools with $t_v \approx t_\infty$ we can write:

$$\frac{a}{D} = 0.85$$

Inserted in (5) and (6) this gives:

Free convection: $Le_n = 0.92$ Forced convection: $Le_f = 0.90$

Simplify the consideration and write in general: $Le = 0.9$ We then get the general convective connection:

$$Le_c = \frac{\alpha_c}{\sigma C_p} = 0.9 \tag{7}$$

The evaporation from the surface in indoor swimming pools is then given in Equations (2) and (7):

$$\dot{m} = \sigma(X_v - X_\infty)$$

$$\dot{m} = \frac{\alpha_c}{0.9 \cdot C_p} \cdot (X_v - X_\infty) \quad \text{[kg/s m}^2\text{]}$$

$$\dot{m} = 1.11 \cdot 10^{-3} \alpha_c (X_v - X_\infty) \quad \text{[kg/s m}^2\text{]} \tag{8}$$

$$\dot{m} = 4\alpha_c (X_v - X_\infty) \quad \text{[g/h m}^2\text{]} \tag{9}$$

The convective heat transfer coefficient is therefore crucial to the evaporation from the water surface. If $p \gg p_m$ we get:

$$\phi = \frac{p_\infty}{p_s} = \frac{X_\infty}{X_s} \tag{10}$$

and Equation (9) is changed to:

$$\dot{m} = 4\alpha_c (X_v - \phi X_s) \tag{11}$$

When determining the convection heat transfer α_c it is natural to differentiate between the two configurations shown in Table 1.

Table 1. Convective heat transfer coefficient for different configurations.

Type of flow	Range	The water in the pool is warmer than the indoor air temperature.	The water in the pool is cooler than the indoor air temperature.
Free	Laminar, $10^5 < Gr \cdot Pr < 2 \cdot 10^7$	$\alpha_c = 1.4\left(\frac{\Delta T}{L}\right)^{1/4}$	$\alpha_c = 0.7\left(\frac{\Delta T}{L}\right)^{1/4}$
convection	Turbulent, $2 \cdot 10^7 < Gr \cdot Pr < 3 \cdot 10^{10}$	$\alpha_c = 1.7 \Delta T^{1/3}$	——
Forced	Laminar, $Re < 10^4$	$\alpha_c = 3.9\left(\frac{\bar{v}}{L}\right)^{1/2}$	$\alpha_c = 3.9\left(\frac{\bar{v}}{L}\right)^{1/2}$
convection	Turbulent, $Re > 10^5$	$\alpha_c = 6.3\frac{(\bar{v})^{0.78}}{L^{0.22}}$	$\alpha_c = 6.3\frac{(\bar{v})^{0.78}}{L^{0.22}}$

In order to determine which α_c is used in the equation for evaporation, we must know the flow conditions at the water surface. We have to determine whether the flow is laminar or turbulent both for free and forced convection.

a) The water is warmer than the indoor air temperature

In Table 1 we anticipate that with free convection the change from laminar to turbulent flow will occur when: $Gr \cdot Pr \geq 2 \cdot 10^7$. For an indoor swimming pool this condition will more or less always be fulfilled as it only requires that $\Delta T > 0.0002°C$. Therefore we conclude that the free convection is turbulent.

In the same way we get turbulent flow in the case of forced convection when $Re \geq 10^5$. For indoor swimming pools this will apply when $v \geq 0.1 - 0.15$ m/s. This is usually the case, i.e. forced flow is also considered to be turbulent. When the water is warmer than the room temperature the flow at the water surface is therefore mainly turbulent.

b) The water is cooler than the indoor air temperature:

From Table 1 we have given that free convection occurs with laminar flow conditions when the water is cooler than the room temperature.

With forced flow the same considerations as in a) will apply, i.e. the flow is mainly turbulent.

The resulting heat transfer coefficients found in the equation for evaporation are calculated from: $\alpha_c = \sqrt{\alpha_n^2 + \alpha_t^2}$. The expression to be used for α_n and α_t is determined according to whether the water is warmer or cooler than the room temperature.

From the expressions included in the heat transfer coefficient (α_c) it follows that where v = 0 m/s and $\Delta T = 0°C$, then also $\alpha_c = 0$. According to Equation 11 this implies that there will be no evaporation. This is clearly incorrect for swimming pools and other liquid surfaces. Evaporation will be caused by diffusion initiated by partial pressure differences and at the same time by differences in density between the air in the room and saturated air at the water surface will generate buoyancy forces which again lead to vertical air motion as drier air comes down towards the water surface.

This last phenomenon can be taken into account by introducing the concept of resulting velocity. This velocity will be made up of a forced velocity w (m/s) and a density velocity u (m/s) occurring because of difference in density between saturated air at the water surface and the overlaying air. We therefore calculate the resulting velocity as:

$$v = \sqrt{u^2 + w^2} \tag{12}$$

The following expression can be derived from [4], showing that saturated air at the water surface will be lighter than the air in the room if:

$$\Phi_\infty < \frac{2644}{p_\infty}\left(1 - \frac{T_\infty}{T_v}\right) + \frac{p_v}{p_\infty} \cdot \frac{T_\infty}{T_v} \tag{13}$$

Buoyancy forces will then generate air motion over the water surface.

The velocity of the rising air motion can approximately be determined from:

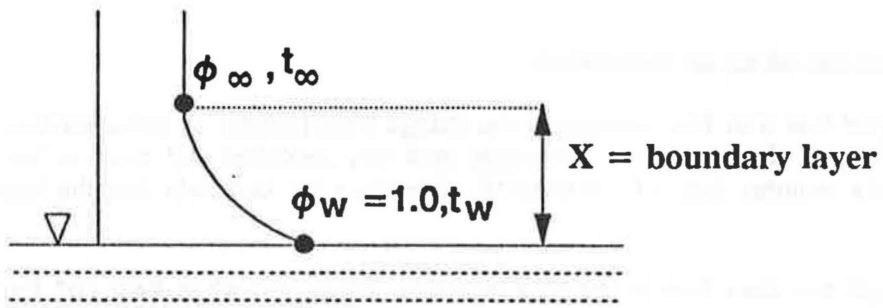


Fig. 2. Boundary layer

$$\frac{\rho_v \cdot u^2}{2} = g \cdot x \cdot (\rho_\infty - \rho_v)$$

$$u = \left(2gx\left(\frac{\rho_\infty}{\rho_v} - 1\right)\right)^{0.5} \tag{14}$$

g = 9.81 m/s, x = 0.2 m (ref (5)) which gives:

$$u = 2\left(\frac{\rho_\infty}{\rho_v} - 1\right)^{0.5}$$

For air pressure of 1 bar we get, from [4]:

$$\frac{\rho_\infty}{\rho_v} = \frac{T_v}{T_\infty} \cdot \frac{349 - 0.132 p_\infty \Phi_\infty}{349 - 0.132 \cdot p_v}$$

For 1 bar and 20°C < t < 35°C saturation pressure and water content can be calculated from:

$$p = 7 \cdot e^{0.06t} \quad \text{[millibar]} \tag{15}$$

$$X = 4.55 \cdot e^{0.06t} \quad \text{[g water/kg dry air]} \tag{16}$$

For conditions that are reasonable in indoor swimming pools, ($p \approx 35$ millibar, $T \approx 300$ K), the expression for density velocity is approximately:

$$\hat{u} = 0.12(4(1-\Phi)-(T_{\infty}-T_{w}))^{0.5} \quad [\text{m/s}] \qquad (17)$$

The validity of Equation (17) is naturally limited by a positive value for the root expression.

When we compare the theoretical expressions for heat transfer and evaporation of water with the measurements in our results and the data given by Hyldgård [5] and Fossdal [6], we can draw up a general semi-empirical expression for evaporation of water from the surface of a swimming pool.

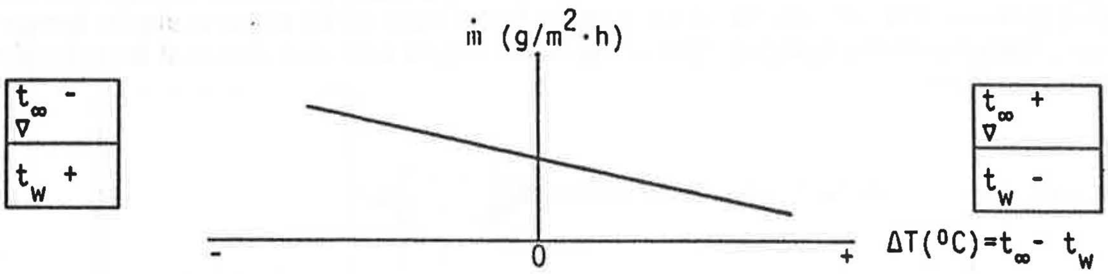


Fig. 3. Water evaporation as a function of the difference in temperature between air and water, principle.

$$\dot{m} = 4\alpha_c(X_w - \Phi X_{\infty}) \quad [\text{g/m}^2\,\text{h}]$$

$$X = 4.55e^{0.06t} \quad [\text{g water/kg dry air}]$$

$$\dot{m} = 18\alpha_c(e^{0.06t_w} - \Phi e^{0.06t_{\infty}}) \quad [\text{g/m}^2\,\text{h}]$$

According to the revealed data in the experimental part of this paper, a general convective heat transfer coefficient can be estimated as: $\alpha_c = 6 \cdot v^{1/3}$, where velocity v is calculated from: $v = \sqrt{u^2 + w^2}$. w is the dynamic velocity in m/s, while u is the term for density velocity given by Equation (17).

If $4(1-\phi) \leq \Delta T$, then $u = 0$, i.e. $v = w$

The general model is then given as:

$$\dot{m} = 108 \cdot v^{1/3}(e^{0.06t_w} - \phi e^{0.06t_{\infty}}) \quad [\text{g/m}^2\text{h}] \qquad (18)$$

If the forced velocity w is low, < 0.1 m/s, at the same time as the temperature difference between the room air and the water surface is great enough, then a "cushion" of calm, saturated air will form over the pool. Evaporation will then have to occur by diffusion instead of by convection. However, this evaporation is very small and may be neglected in most cases.

Description of the Swimming Pool and its Technical Installations

The measurements were taken in Trondheim, at an indoor swimming pool owned by the Norwegian Union for the Blind. The pool measures 12 x 6 m (72 m^2). The drainage area round the pool totals approximately 15 m^2 and the area for walking 59 m^2. The height of the ceiling is 2.5 m.

Air for ventilation enters the room through slots under the windows along the west facade and from slots in the ceiling along the east wall. The return air grille is situated below the ceiling on the east wall.

The ventilation plant is installed in the basement. In addition to the supply and return air fans the aggregate consists of an air recirculation unit filter, dampers and an electric heating unit. The heating unit is responsible for constant air temperature in the room while the recirculation dampers are to ensure constant relative humidity (RH) in the room. Figure 4 shows a sketch of the principles of the ventilation plant.

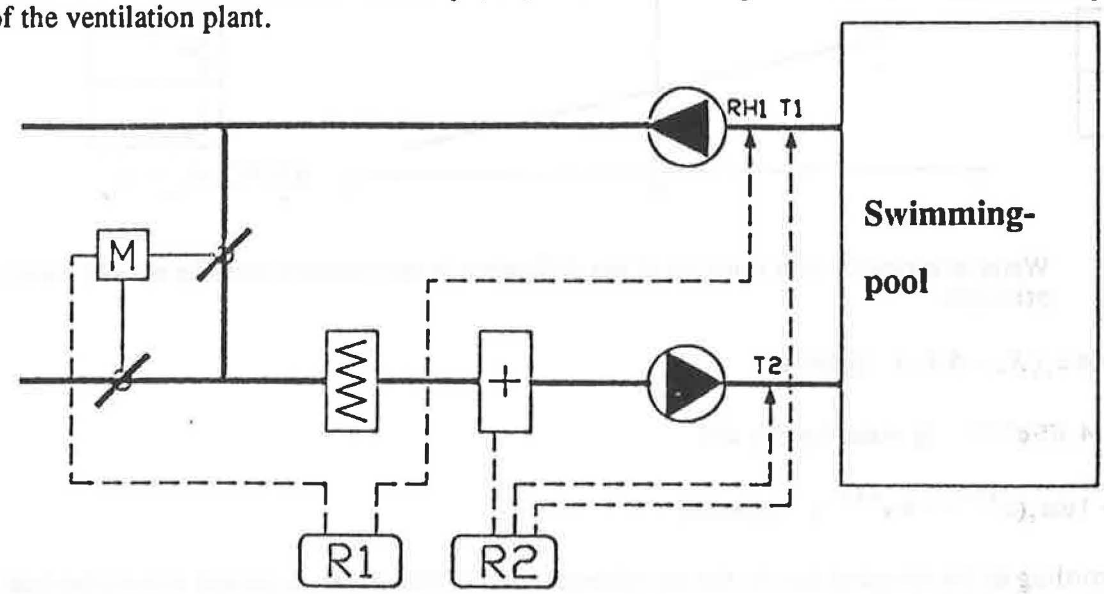


Fig. 4. Sketch of principles of the ventilation plant.

The pool is hired out a great deal, which means that there is considerable variation in the number of people bathing and in the level of activity. The various groups that use it include rheumatics, kindergarten children, school classes, mentally handicapped people, firms and sports clubs. The temperature of the water may seem rather high: it is usually between 31°C and 34°C for the sake of the elderly and rheumatics.

Collection of Data

Measurements of the amount of vaporized water were made by continual registration of temperature and relative humidity in the air taken in and extracted. At the same time the temperature and humidity of the outside air were also registered, as was the temperature in the pool. Figure 5 is a sketch showing the principles used for the measuring system.

Data was collected at 2-second intervals. It was then averaged and printed out for periods of 10 minutes.

The above measuring system gives us the amount of vaporized water in g/kg of ventilation air, and the degree of air recirculation of the aggregate. When the amount of air is known, evaporation can be calculated. The amount of air was measured manually according to different positions of the air recirculation damper.

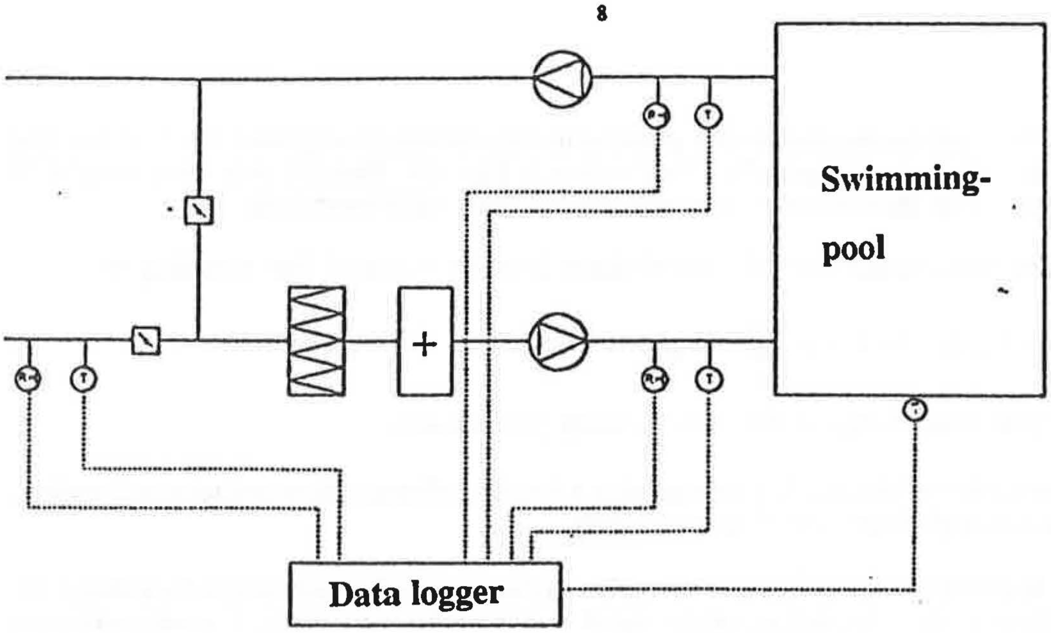


Fig. 5. Sketch showing the principles of the measuring system.

If this system is to register evaporation correctly, it is necessary to avoid condensation on the surfaces of the room and to remove all the moist air through the ventilation system.

The first of these requirements was fulfilled by manual inspection and the second by using tracer gas analysis. Tracer gas measurements showed that there was no exfiltration and that the ventilation air was used effectively.

Photographs were taken automatically at 20-minute intervals to register activity and load. The weakness of this method is that it may be difficult to take the level of activity into account on the basis of photographs. As the method does not give any information either about how much of the walking area was wet, it was supplemented by manual observations.

The last parameter that must be measured is the air velocity above the water surface. This was measured manually at a number of points by traversing. Large fluctuations of velocity and extremely low velocity make great demands on the measuring equipment. A typically mean velocity measured was $\bar{v} = 0.16 \pm 0.05$ m/s based on 21 equally distributed measuring points.

Results

In order to evaluate increased evaporation caused by human load it is necessary to keep other parameters affecting evaporation constant. This involves a number of problems, including the following:

- how to measure activity
- whether children and adults cause the same increased evaporation
- how to take account of the wet walking areas
- how to compensate for inaccurate control (room temperature + relative humidity)
- what to do about periods of activity which are too short to attain steady state conditions

Several of these points can only be clarified by using detailed parameter studies. The last two can be solved by ignoring data where the conditions are not certain.

It is possible to present the course of evaporation in the swimming pool graphically by processing data collected manually and automatically. This is done in Figure 6. Here the evaporation in $g/m^2 h$ is drawn as a function of the room condition, water temperature and human load.

The amount of vaporized water G was calculated from the measured data according to:

$$G = \dot{m}_e X_e - \dot{m}_a X_a - \dot{m}_s X_s + \rho V \frac{dX_e}{dt} \quad [kg/h]$$

The last term is the change in the room humidity per time unit.

The water content of the air, X, is expressed as a function of temperature and relative humidity. This is found for example in the use of an hx-diagram.

In order to find the evaporation as a function of relative humidity and temperature difference between air in the room and the pool, several series of measurements were made. For each series one or more of the parameters water temperature, air temperature or relative humidity were altered. Each series lasted about one week.

The tests were planned as a fraction of an orthogonal first order design with one additional measurement in the centre point. However, because of the users' requirements for the temperature of the water in the pool it was not possible to follow this plan completely. Table 2 lists the actual tests that were carried out.

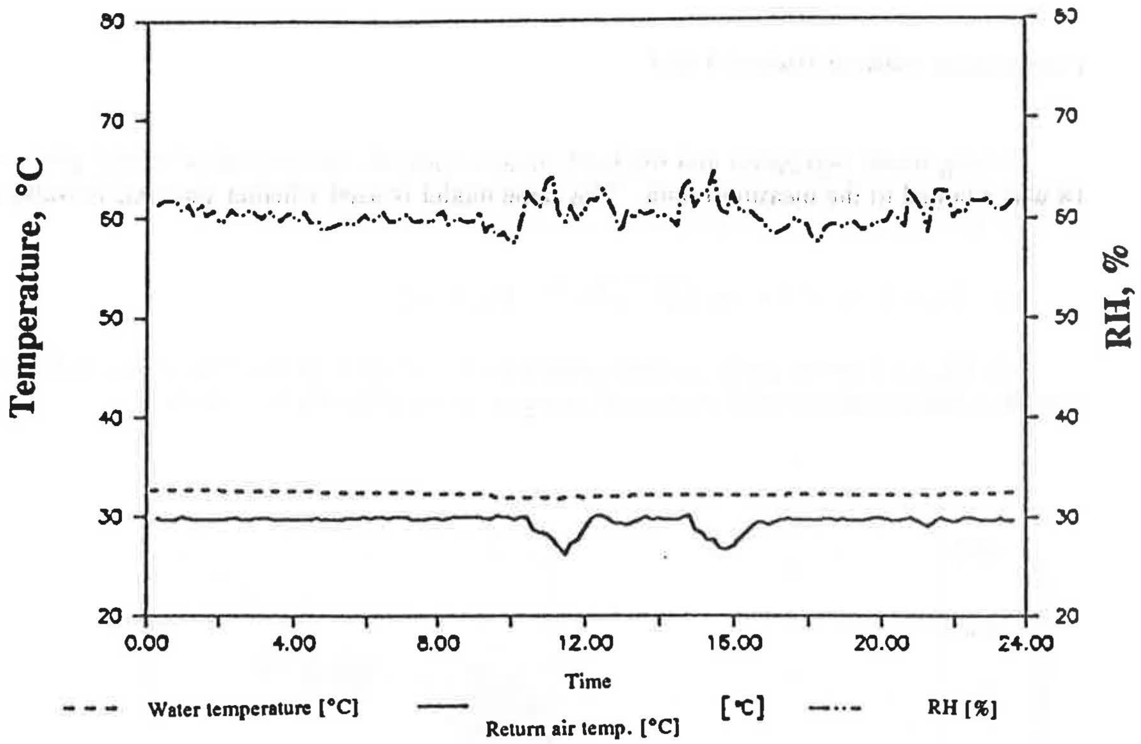
Table 2. Tests carried out

Test no.	Room air temperature ^oC	Water tem-perature ^oC	ΔT	Relative humidity %
1	29	34	-5	60
2	29	32	-3	40
3	32	32	0	50
4	30	32	-2	40
5	33	31	2	40
6	33	33	0	35
7	33	34	-1	30

The values given here are not exact, as conditions changed slightly in the course of the test series.

The reason for the limitations concerning the temperature is that the pool is used for therapy two days a week. The thermal storage of the water also limited how far the water temperature could be lowered during the intervening periods. In addition to this the temperature level of the inside air is limited by how much thermal stress people can bear and how high the air temperature can be raised.

The whole of Test Series 2 had to be disregarded because of great fluctuation of the intake air temperature. The same applied to parts of the other test series.



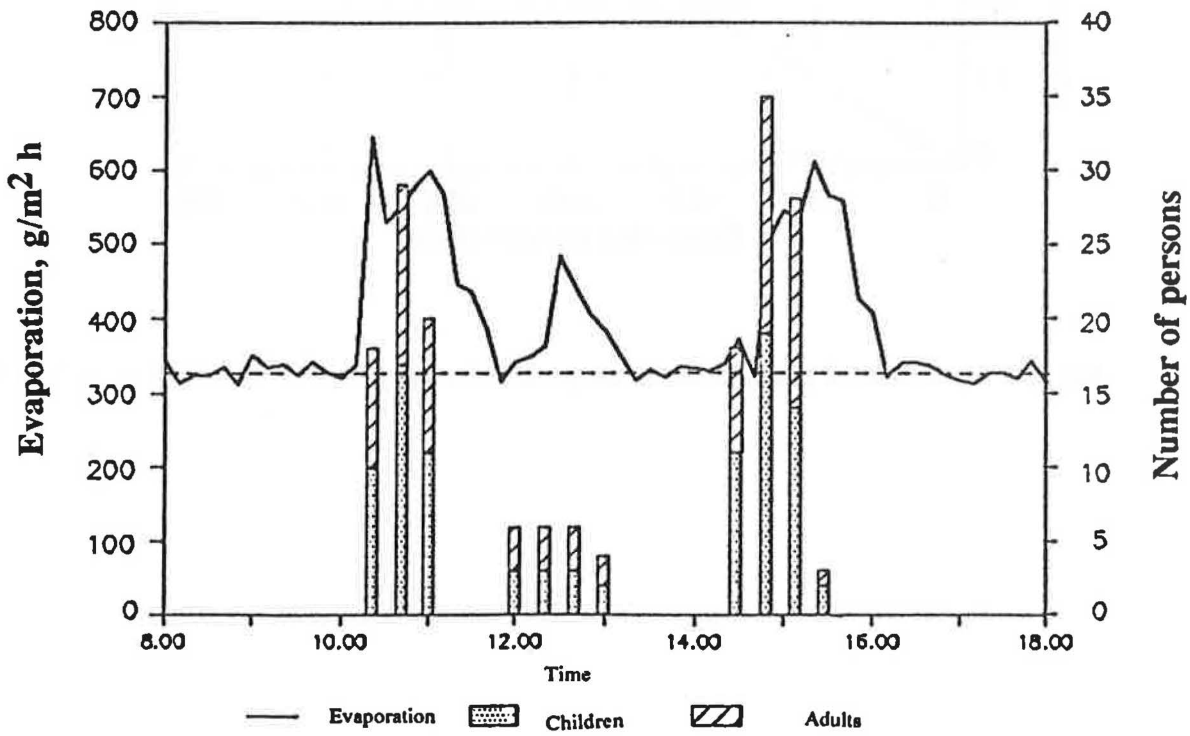


Fig. 6. Examples of measured values. Maximum measured additional evaporation due to activity.

Evaporation without Human Load

Using linear regression and the least squares method, the theoretical model given in Equation 18 was adapted to the measured data. The same model is used whether the pool is cooler or warmer than air temperature. The evaporation coefficient in the model is given by:

$$\sigma = 4\alpha_c = 4 \cdot 6 \cdot v^{1/3} = 24(\sqrt{u^2 + w^2})^{1/3} \quad \text{[kg/h m2]}$$

In Figure 7 the model is plotted against the measured data and it is shown in Figures 8 and 9 how the model conforms with measured evaporation for different ΔT and Φ.

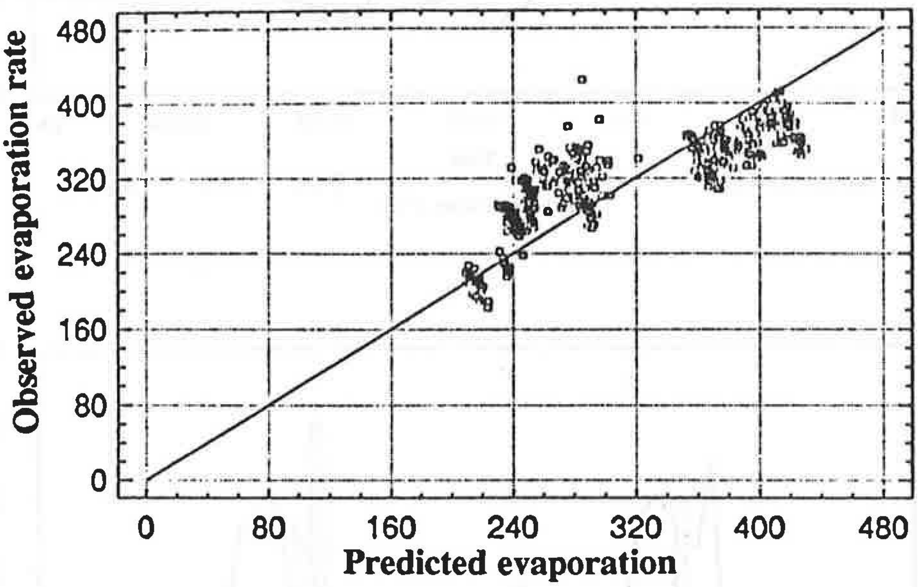


Fig. 7. Observed evaporation versus predicted evaporation. Evaporation g/h m² pool surface.

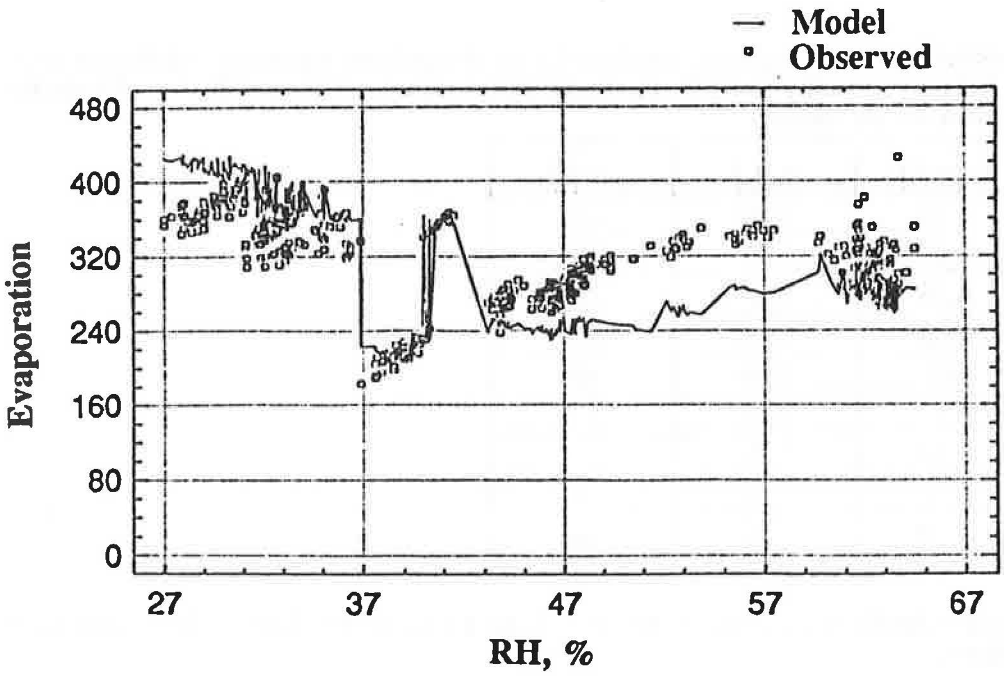


Fig. 8. Relative humidity versus observed and predicted evaporation.

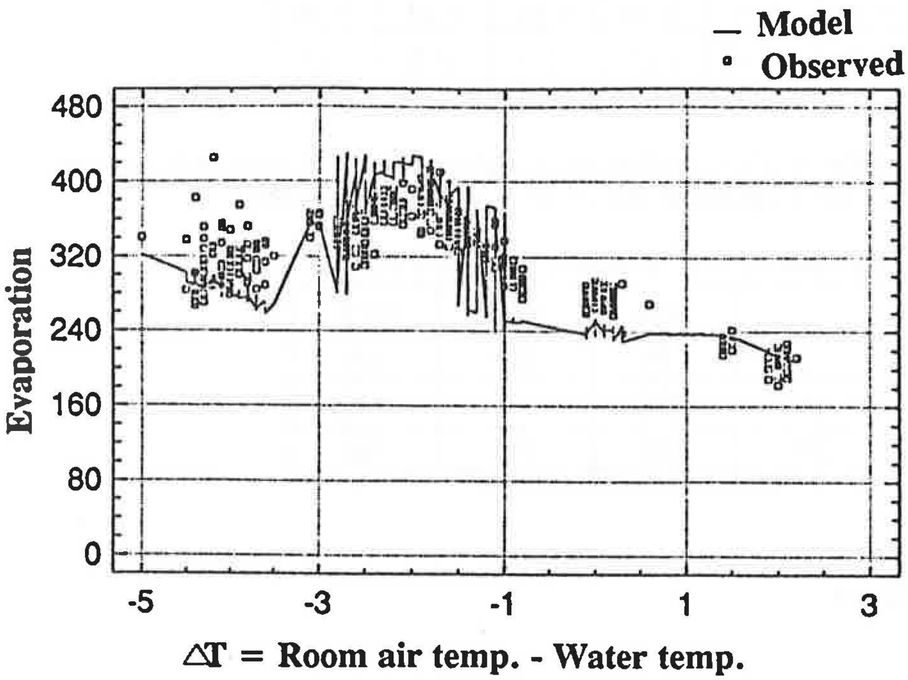


Fig. 9. ΔT versus observed and predicted evaporation.

Table 3 lists some values of calculated velocity, heat transfer coefficient and vaporized water mass flow rate using the above equations.

The table shows that while the total evaporation varies from about 100 (g/m2 h) to 240 (g/m2 h), the evaporation coefficient σ(represented here as α_c) increases by about 50%. This shows clearly how wrong it is to operate with the constant evaporation figures that we sometimes see recommended for swimming pools.

Table 3. Calculated values for velocity, heat transfer coefficient and vaporized water mass flow rate. Relative humidity is 50 %, the water temperature is 28°C and the forced velocity is 0.1 m/s for all values.

t_{-}[°C]	υ [m/s]	α_c[ ]	$\dot{m}$[ ]
24	0.31	4.06	238
25	0.29	3.95	222
26	0.26	3.83	206
27	0.23	3.68	188
28	0.2	3.49	169
29	0.17	3.23	146
30	0.10	2.79	117
31	0.10	2.79	10
32	0.10	2.79	98

If the resulting velocity approaches 0, there will be a significant drop in the evaporation coefficient, see Table 4.

Table 4. Examples of resulting velocities and evaporation coefficients.

$\upsilon = \sqrt{u^2 + w^2}$, [m/s]	0.0	0.05	0.10	0.15	0.20	0.30
σ [kg/h m^2]	0.0	8.8	11.1	12.8	14.0	16.1

Table 5 shows other examples of evaporation calculated by the help of the model. As it can be seen the relative humidity also has a significant influence on resulting evaporation.

Table 5. Evaporation from pool (g/h m^2 pool area). Pool temperature = 28^{o}C, w = 0.15 (m/s)

Relative humidity		30 %	45 %	60 %
Indoor air temperature, [^{o}C]	26	286	230	176
	28	256	196	139
	30	218	155	100

Evaporation with Human Load

Activity in the room increases evaporation. Our hypothesis is that the evaporation can be expressed by three terms:

1. Evaporation from the surface of pool
2. Evaporation from spray and parts of body above water
3. Evaporation from water splashed on the floor

For Term 1 the connection described in Section 4.1 is used. For Term 2 an enlargement factor is added to Term 1. For Term 3 the floor temperature and the water temperature are assumed equal to indoor air temperature. The same expression used in Term 1 is then applied.

The following weighting of the factors may be a useful model for the evaporation measured:

$$\dot{M} = \dot{m}_{pool}\left(1 + \frac{Area\ per\ person \cdot number\ of\ persons}{pool\ \ area}\right) + \dot{m}_{floor} \tag{19}$$

$\dot{m}_{floor}$ is determined according to the wet floor area. A reasonable estimate for area of persons could be 0.5 m^2 per person.

In this study it was not possible to differentiate between the various activities and groups of users on the basis of the measurements taken. Because of scattering in the measurement data and relatively few measurements, statistically significant differences cannot be demonstrated. However, some conclusions can be drawn. The mean level for all groups shows an increase of evaporation owing to activity of 56 g/h m^2. Furthermore the maximal additional evaporation seldom exceeds 150 g/h m^2. These results are interesting because we observed that the evaporation increased sharply when one or a few persons entered the pool. Additional users only raised the evaporation load slightly, i.e. we have a kind of step-function. The explanation is probably that a wet floor is a significant factor with regard to the total evaporation. It seems that it only takes a few persons to make the mostly used area around the pool wet. Extreme evaporation probably occurs when surfaces which usually are not moistened become wet.

We assume a situation where the total floor area round the pool is wet to be a designed condition. This additional evaporation is shown in Table 5.

Table 6. Evaporation from floor (g/h m^2 wet floor area) Water temperature on floor = indoor air temperature

Relative humidity		30 %	45 %	60 %
Indoor	26	227	174	123
air temperature	28	256	196	139
[°C]	30	288	221	156

Concluding Remarks

- It has been shown that the suggested semi-empirical model for evaporation from a pool that is not in use gives a satisfactory description of the evaporation.
- One or a few bathers gives a significant increase in the evaporation. A further increase in the number of bathers only gives a small additional contribution to the evaporation since only a small number of bathers is needed to moisture the surfaces around the pool. However, it has not been possible to differentiate between different levels of activity and different numbers of bathers.
- Large wet areas of the floor will affect the design of the ventilation plant and the total evaporation from the swimming pool.

Acknowledgements

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SUMMARY

In order to determine the economically optimum quantity of air and components in a ventilation system it is necessary to know the evaporation rate as a function of the temperature of the room and the water, the relative humidity and the level of activity. In the literature several methods are given for calculating this evaporation. However, as these produced completely different results, full-scale measurements were required in order to provide a better model for evaporation from swimming pools.

- It is shown that a suggested semi-empirical model for evaporation from a pool that is not in use gives a satisfactory description of the evaporation rate.
- One or a few bathers gives a significant increase in the evaporation rate. A further increase in the number of bathers only gives a small additional contribution to the evaporation rate since only a small number of bathers is needed to moisture the surfaces around the pool. However, it has not been possible to differentiate between different levels of activity and different numbers of bathers.
- Large wet areas of the floor will affect the design of the ventilation plant and the total evaporation rate from the swimming pool.