Effect of Air Velocity on Water Evaporation Rate in Indoor Swimming Pools

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This paper focuses on an experimental investigation of the water evaporation rate into the moving air currents of indoor swimming pools. A series of experimental measurements have been carried out to investigate the effects of different parameters on the evaporation rate from water surface. Based on experimental measurements, a new correlation has been attained for the water evaporation rate into the moving air. The new empirical correlation indicates a functional relationship between the exponent of vapor pressure difference and the air stream velocity. The predictions of the new approach gives good agreement with measurements. The comparison between water evaporation rates from free water surface and wetted surface shows that for low air velocities, evaporation rate from wetted surface is higher than that of free water surface and for high air velocities, it is reversed.

Keywords: water evaporation rate; air velocity; wetted surface

1 Introduction

The phenomenon of water evaporation into air is important from heat and mass transfer view point and it exists in many applications such as water purification plants, swimming pools, cooling ponds, solar stills, drying, air conditioning and nuclear engineering. The evaporation from a water body is the result of two process: forced evaporation due to the flow of air across the water surface and free evaporation (evaporation to still air) caused by the density difference of moisture between the air just above the water surface and the surrounding air. In many systems such as swimming pools the evaporation from free water surface and wetted surface is often caused by a combination of both forced and free evaporation components. In indoor swimming pools, due to conventional ventilation there is a small but significant amount of forced convection over both the water surface and wetted surfaces.

Considerable efforts have been made to predict the correlation of water evaporation rate from free water surface into the both still and moving air[1-4]. The expressions that have been proposed by the researchers for the evaporation rate are very complicated and induce the effects of airflow above the water surface and the difference in vapor pressure of water at its surface temperature and that in the surrounding air dew point. The majority efforts in the past have been made to collect data from outdoor evaporation. Sartori [1] investigated the solar evaporation rate from outdoor large free water surface. Lam and Chan [3] studied the thermal performance and energy cost of an outdoor roof top swimming pool. Tang and Etzion [4] compared the evaporation rates from free water surface and wetted surface to the outdoor ambient air. More investigations are needed to determine which correlation can be considered reliable to predict evaporation rates for indoor moving air streams.

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In indoor swimming pools excessive humidity is a problem and the air change volume rate considerably affect the evaporation from water pool surface and energy losses [5,6]. Limited investigations have been conducted to obtain reliable methods for prediction of evaporation from indoor pools [7,8]. The present study of evaporation measurements has been motivated by the need to increase accuracy of predictions of the evaporation in indoor swimming pools. The aim of this study is to investigate the effects of a wide range of indoor pool parameters including air velocity, water temperature, relative humidity and vapor pressure difference on the evaporation from free water pool surface and from wetted surface. In addition, a new correlation is attained for calculating the detailed effects of air velocity on the water evaporation rate into the moving air.

2 Mathematical correlation of evaporation rate

Based on many experimental measurements [4,5], the most widely published and used mathematical correlations of water evaporation rate are the expressions that proportionate the rate of evaporation to: a) the difference in vapor pressure at the surface of water and that in the air dew point temperature, and b) the velocity of the air. The general form of these empirical correlations for water evaporation rate into the air moving with v as air velocity is as follow [1]:

$$\dot{m}_e = \left(C_1 + C_2 V\right)\left(P_W - \phi P_S\right) / h_{fg} \tag{1}$$

Intense efforts have been made to determine coefficients C_1 and C_2 which result from multiple parameters embedded in the values of the coefficients, such as area of water bodies and their shapes. The literature survey shows several reported values for C_1 and C_2 [1,4]. The discrepancies between the values of the coefficients C_1 and C_2 may partly be a result of the fact that water evaporation rate is not a simple linear function of the vapor pressure difference $\left(P_W - \phi P_S\right)$ [4]. The results obtained by Pauken [9] shows that the evaporation rate for fixed air velocity does not increase linearly with vapor pressure differential. This implies that the water evaporation rate may relate to exponent of vapor pressure difference:

$$\dot{m}_e = \left(C_1 + C_2 V\right)\left(P_W - \phi P_S\right)^n / h_{fg} \tag{2}$$

Many investigators have used n as constant [1]. The data analysis of this study showed that the power n was a function of air velocity. Air flow across a flat plate will develop thermal and concentration boundary layers. Dimensional analysis on the convective energy and evaporation process and their respective boundary conditions results in the same dimensionless form for equations and boundary conditions [2]. Advection to the flat plate is governed by the Re number; diffusion is characterized by Pr number [see eq. 3] and by Sc number [see eq.4]:

$$U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial z} = \frac{1}{\left(\mathrm{Re}_L\right)\mathrm{Pr}}\frac{\partial^2 T}{\partial z^2} \tag{3}$$

$$U\frac{\partial C}{\partial x} + V\frac{\partial C}{\partial z} = \frac{1}{\left(\mathrm{Re}_L\right)Sc}\frac{\partial^2 C}{\partial z^2} \tag{4}$$

The above mentioned dimensionless groups have important roles on experimentally and theoretically investigation of water evaporation. The definition of $Nu = \frac{hx}{k} = f(\mathrm{Re}, \mathrm{Pr})$ and $Sh = \frac{g_{m,H2O}}{\rho D_{H2O,air}} = f(\mathrm{Re}, Sc)$ are used for heat transfer and mass transfer respectively. The binary diffusion coefficient $D_{H2O,air}$ for water vapor through air is calculated from [10]:

$$D_{H2O,air} = 1.87 \times 10^{-10} \left(\frac{T^{2.072}}{P} \right) \tag{5}$$

The mass transfer coefficient $g_{m,H2O}$ is defined by analogy to heat transfer as [10]:

$$g_{m,H2O} = \frac{\dot{m}}{mf_{H2O,S} - mf_{H2O,R}} \tag{6}$$

where the mass fractions of water vapor are calculated as functions of vapor mole fraction $X = P_{H2O}/P_{atm}$:

$$mf_{H2O,S} = \frac{(X_{H2O,S})(18.02)}{[(X_{H2O,S})(18.02) + (1 - X_{H2O,S})(28.96)]} \tag{7}$$

$$mf_{H2O,R} = \frac{(X_{H2O,R})(18.02)}{[(X_{H2O,R})(18.02) + (1 - X_{H2O,R})(28.96)]} \tag{8}$$

and according to the values tabulated by Incropera and Dewitt for moist air [11], the relation between the temperature and saturation vapor pressure for the temperature values used in this study is calculated by:

$$P_{H2O} = 338.5.5 \exp\left[-8.0929 + 0.97608(T + 42.607)^{0.5}\right] \tag{9}$$

In indoor swimming pools, in addition to free convection caused by the density difference, due to the operation of air conditioning system, there is a small forced convection. The type of the convection mechanism is determined by [10]:

$$Gr_l / R_e^2 = \left(\frac{Ra^{1/4}}{Re^2\, Pr^{1/3}} \right)^4 Pr^{1/3} \tag{10}$$

The results of experimental measurements showed that for the values of air velocity between 0.1 and 0.3 m/s (used in indoor swimming pools), $Gr_l / R_e^2 \approx 1$. This shows that in indoor swimming pools free and forced convection effects are comparable. This is consistent with the results of Liu et al. [5] and Paukan [9]. In this case, the Sherwood number for mixed convective operation is given by [12]:

$$Sh_{total} / sh_{free} = \left[1 + \left(\frac{Sh_{force}}{Sh_{free}} \right)^a \right]^{1/a} \tag{11}$$

where the exponent a can have a value between 1 and 2 [9,11]. In indoor swimming pools turbulent conditions are easily generated by air conditioning of the pool and the Sherwood numbers for turbulent free convection ($Grm\ Sc>2\times10^7$) evaporation regimes and turbulent forced convection ($Re_l>5\times10^5$) evaporation regimes are defined as follows [9]:

$$Sh_{free} = 0.14(Gr_m\ Sc)^{1/3} \qquad Sh_{force} = 0.036Sc^{1/3}\,\mathrm{Re}_L^{\ 0.8} \tag{12}$$

3 Experimental test Chamber and measurements

The water evaporation measurements were carried out in a test chamber with internal dimensions of 150×100×100 cm. The evaporation pond of test chamber was 25 cm deep and had 5 electric heaters located at the bottom and on the walls to maintain water at elevated temperatures. All surfaces of the chamber and evaporation pond were insulated with 5 cm polystyrene panels to reduce heat loss. The air and water temperatures were measured by 8 thermocouples located 1 cm under the water surface and at different points of the chamber space. The relative humidity was measured by 6 measurement points. A simple sketch of test chamber and its essential features is presented in Figure 1. Data from water and air temperature and also relative humidity was recorded by a personal computer data acquisition system. All sensors were calibrated before measurements.

The test chamber was located at a large laboratory. The laboratory had a controlled air conditioning system to maintain the air at constant temperature and relative humidity. The inlet air temperature of the test chamber was controlled to maintain at 45 °C (based on conventional air conditioning systems). The air of the chamber was exhausted to outside by a centrifugal fan. The fan acted as a draw-thru unit (induced fan arrangement) to reduce the turbulent effects of air current on evaporation rate. Testo-405 anemometer with accuracy of 1% was used to measure the airflow rates through the chamber.

The water evaporation loss was measured by using the method of Pauken [9]. In this method, the water evaporation loss is determined by connecting the evaporation pool to a small pan that rested on a digital scale through a siphon (Figure 1). The accuracy of the scale was 0.1g. The water loss in the evaporation pool is proportion to the mass change in the small weighing pan. The proportional constant is determined by removing a measured mass of water from the water pool and recording the change in mass on the scale. Twenty observations revealed that an average of 55±0.1 g of water was removed from the water pool for 1g change on the scale. For measuring water evaporation rate from the wetted surfaces, the method of Tang and Etzion [4] was used. White towels were stretched over a densely perforated PVC panel supported by pieces of waterproof polystyrene to make the towels float on the water surface of the pond.

4 Discussion and results

As water loss due to evaporation was very slow, in order to accurately measure the change of water weight in the evaporation pond, the measurements were carried out on an hourly basis time interval and for a 12 hours period. The data analysis included averaging the measured quantities over the full measurement period.

Figs. 2 shows the effects of water temperature and air stream velocity on free water surface evaporation rate. Very low evaporation rate is observed for water temperatures lower than indoor ambient air temperature (30°C) and low air velocities. This is in accord with wind tunnel based measurements of Pauken [9]. It can be seen that for higher water temperatures, the evaporation rate is considerably affected by water temperature and air current velocity. The figure shows that an increase in water temperature/air velocity increases the evaporation rate.

Figure (3) presents the comparison between the measured evaporation rates from free water surface and that from wet cloth surface for different values of water temperature air current velocities. The primary result of this comparison is that the evaporation rate from free water surface and that from wetted surface are different. Many investigators have assumed that the water evaporation rate from the wetted surfaces is similar to that of free water surface. The figure shows that for low air velocities (air vel.< 0.3 m/s, which usually occur in indoor swimming pools), the evaporation rate from wet cloth surface is greater than that from free water surface. This occurs because the rough wet cloth surface has a greater surface area in contact with the surrounding air in comparison with smooth free water surface. For relatively high air velocities, the condition is reversed. This occurs because the rough surface of wet cloth which increases the friction between the air and evaporating surface, creates a thicker boundary layer of vapor concentration. These results are in accord with experimental measurements of Tang and Etzion [4] in outdoor ambient.

Figure (4) shows the effect of vapor pressure difference ($\Delta P = P_w - P_s$) on evaporation rate for three air stream velocities. ΔP is the difference of vapor pressure at the surface of water (the saturated pressure corresponding to the water surface temperature at a relative humidity of 100%) and that in the air (the air dew point temperature which is calculated from equation 9). To introduce the correlation of water evaporation into the moving air currents in the form of equation 2, a non-linear regression analysis using Spass soft ware suggests a mathematical model of the form:

$$\dot{m} = (0.0038 + 0.1356V)(P_w - \phi P_S)^{(-1.255V^3 + 2.182V^2 - 1.362V + 1.377)} \quad , \quad \delta = 8.5 \qquad (13)$$

The error δ is due to the proportionality constant for weighing pan and the resolution of scale during long time data collection period. With free convection evaporation, the exponent takes the value 1.377 which shows good agreement with the results of other investigators [7,9]. In this figure, the predicted evaporation rates calculated by equation 13 (solid lines) are compared with measurements for three air stream velocities. It can be seen that the equation 13 reproduces the important features of evaporation rates and show reasonable quantitative agreement with the experiments. The figure also shows that the water evaporation rate variations with the vapor pressure difference depend on the air velocity. The comparison between the results of the present study with experimental measurements of Smith [13] shows good agreement (Figure 5).

Figure (6) displays the comparison between the variation of exponent n (as a third order decreasing function of air velocity) attained in this study with the constant values used by Paukan [9] and ASHRAE [14]. The curve shows that an increase in air velocity decreases the value of n. In fact, although an increase in air velocity decreases the value of n, but due to increase in vapor pressure difference the evaporation rate enhances. The empirical correlation (eq. 12) suggested in this study is based on the measurement of evaporation from a relatively small indoor free water surface and the issue of relationship of n with size and wetted surfaces needs further investigation.

Figure (7) displays the measured dependence of total evaporation rate on the ratio of forced to free convection. Here, Sh(total)= Sh(free)+ Sh(forced). The free and forced convection components of Sherwood number are calculated from equation 12. Attention is now paid to find the optimal value of exponent a in equation 12. Using a lot of trail-measurement results and repeating the non-linear regression for different values of a, it is found that the best fit value of a (in equation 12) to all measurements is a =1.075 with coefficient of determination R^2=0.93:

$$Sh_{total} / sh_{free} = \left[1 + \left(\frac{Sh_{force}}{Sh_{free}} \right)^{1.075} \right]^{1/1.075}$$

Figure (7) shows that considerable variation exists in predictions of available correlations for water evaporation into moving air currents. The maximum discrepancy is about 20 %. The differences in these correlations can be attributed to the error of experimental measurements, the size effects of test chamber and the error of the weight of added water. This result is in agreement with findings of Pauken [9]. The "a" values that obtained by Pauken are between 1 and 2.

5 Conclusions

In indoor swimming pools due to high rates of water evaporation and ventilation losses with exhaust air, reliable correlations for the prediction of evaporation and estimating energy demand are needed. A series of experimental measurements have been carried out in a test chamber to develop a functional relationship between indoor water evaporation rate and the air stream velocities. Based on the presented results, the following conclusions may be drawn:

1- Regression analysis shows that the measured evaporation rates have strong dependence on air velocity (Re number) and Sherwood number.
2- The best non-linear fit to measure data indicates a third order decreasing functional relationship between the exponent of vapor pressure difference and water evaporation rate.
3- The comparison between water evaporation rates from free water surface and wetted surface shows that for low air velocities, evaporation rate from wetted surface is higher than that of free water surface and for high air velocities, this is reversed.

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Nomenclature

a	power of exponent	P_S	water vapor partial pressure at the air temperature (Pa)
C_1,C_2	coefficients of empirical equations	P_W	water vapor partial pressure at the water temperature (Pa)
D	mass diffusivity ($m^2 s^{-1}$)	Re	Reynolds number
g_m	mass transfer coefficient	Sc	Schmit number
Gr_m	mass transfer Grashof number	Sh	Sherwood number
h_{fg}	latent heat of vaporization of water (Jkg^{-1}	V	air velocity (ms^{-1}).
$\dot{m}$	evaporation rate ($kgm^{-2}s^{-1}$)	X	mole fraction
mf	mass fraction		*Greek letters*
n	power of exponent	δ	standard deviation, g
N_u	Nusselt number	μ	dynamic viscosity ($kgm^{-1}s^{-1}$)
P	atmosphere pressure (Pa)	ρ	density (kgm^{-3})
P_r	Prandtl number	ϕ	Relative humidity

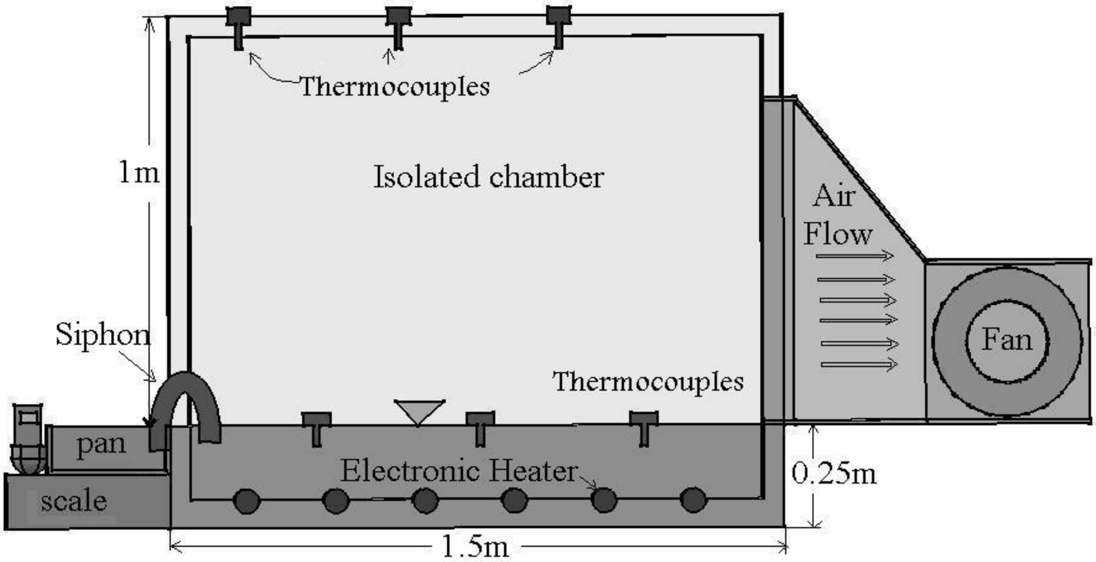

Figure 1 Experimental test chamber and its essential features

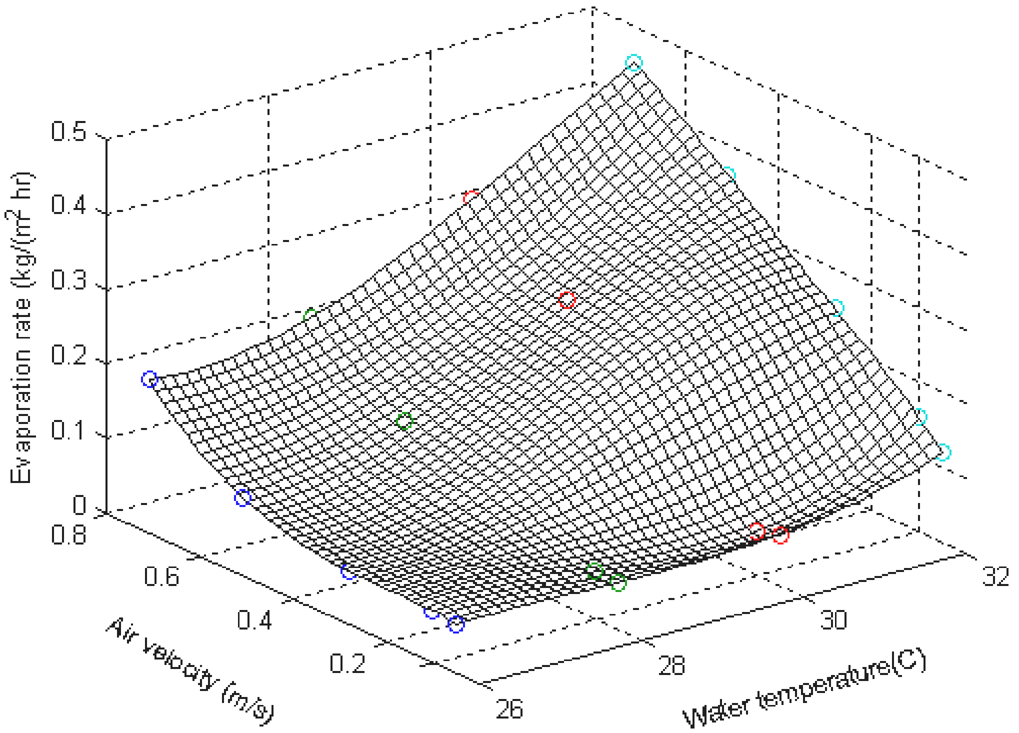

Figure 2 Effect water temperature and air velocity on free water surface evaporation rate

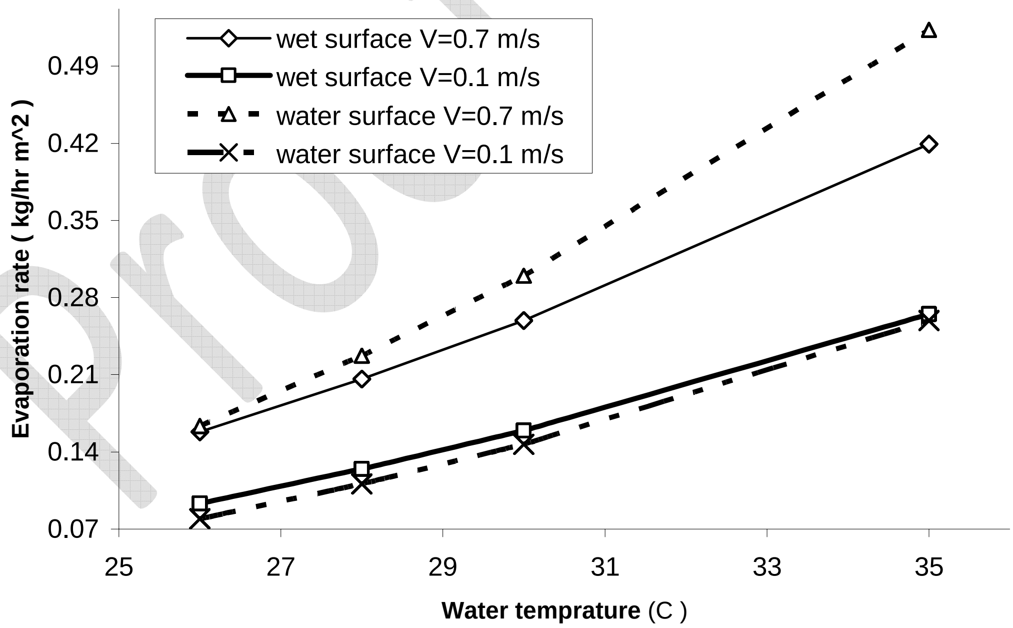

Figure 3 Comparison between evaporation rate from free water surface and that from wet surface

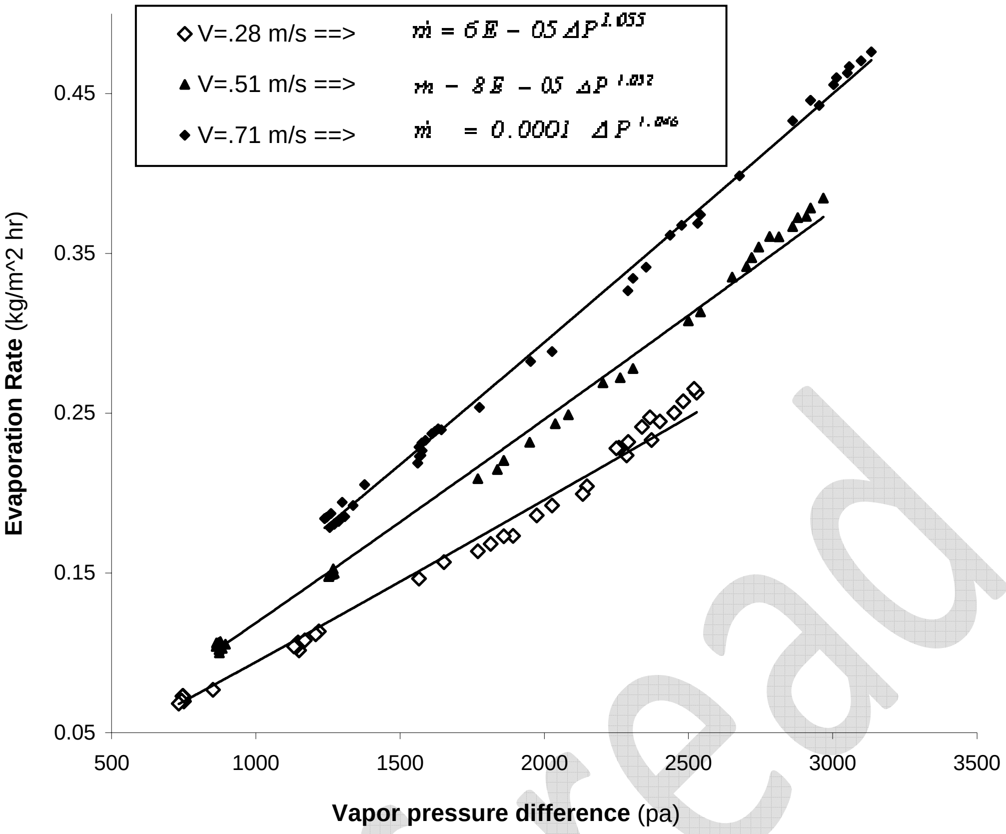

Figure 4 Effects of vapor pressure difference and air velocity on water evaporation rate

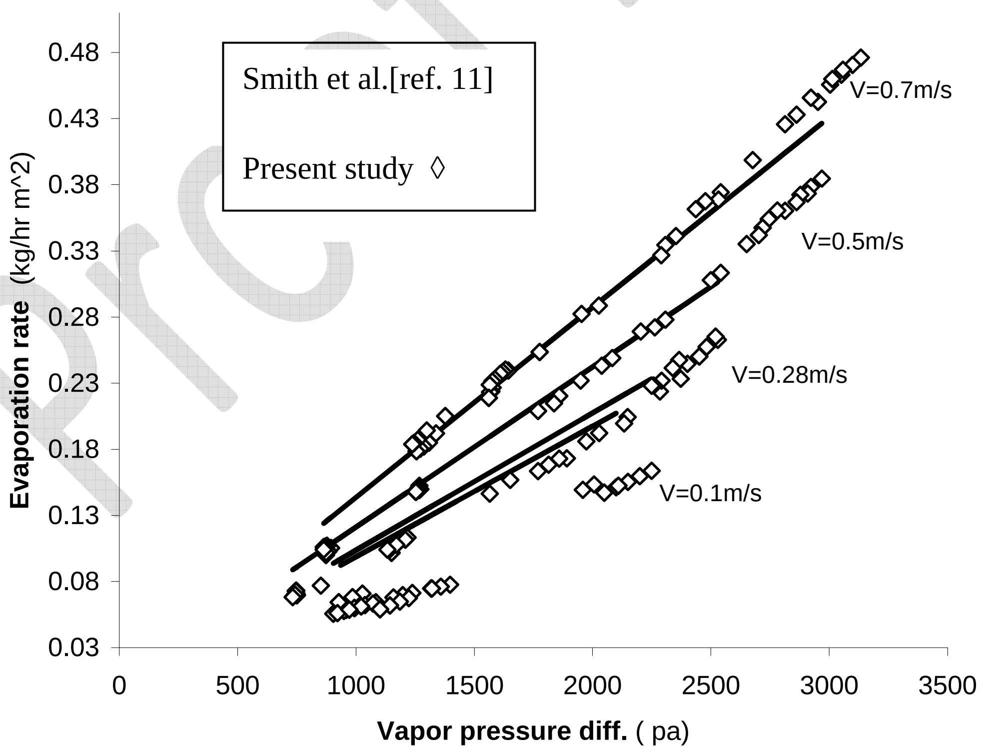

Figure 5 Comparison of correlation of Smith et al. [11] with data from this study

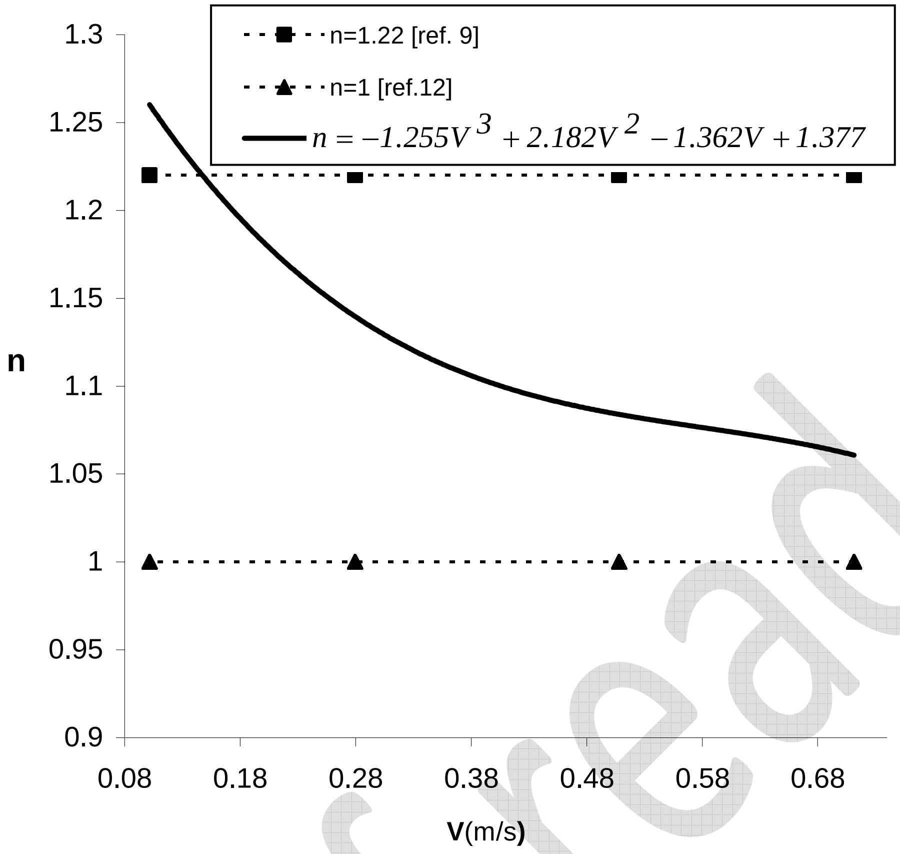

Figure 6 Effect of air velocity on variation of exponent (n)

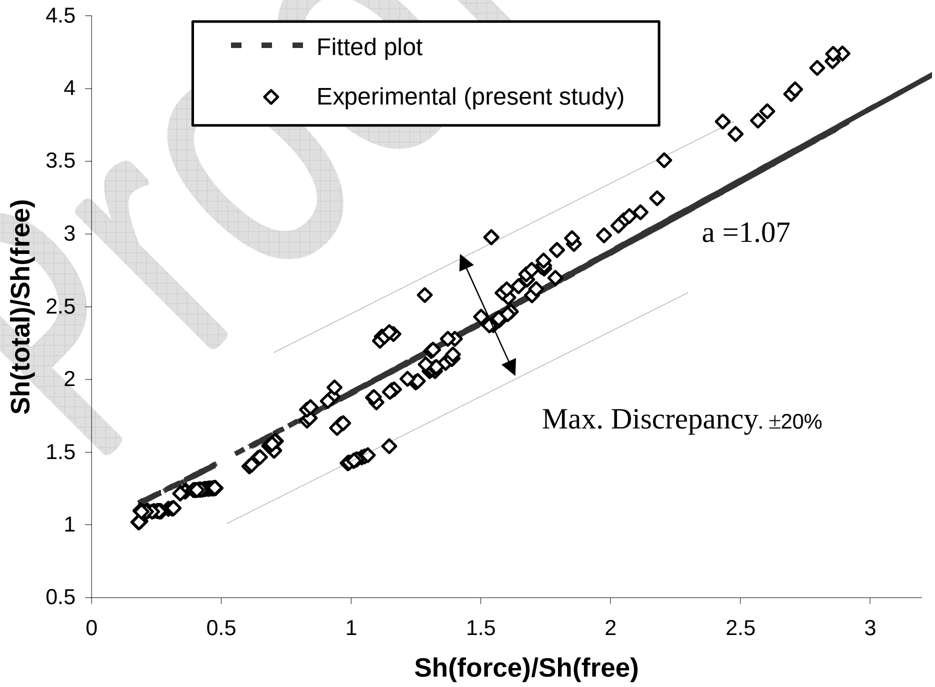

Figure 7 Variation of total evaporation rate as a function of forced to free convection ratio

چکیده:

در این مقاله به روش اندازه گیری آهنگ تبخیر آب به داخل جریان هـوا در اسـتخرهای سـر پوشـیده مـورد بررسی قرار گرفته است. با انجام آزمایشات متعدد اثر عوامل مختلف بر مقدار تبخیر از سطح آب اندازه گیـری گردیده است. بر پایه نتایج حاصل از اندازه گیری ها، یک رابطه جدید برای آهنگ تبخیر آب به داخل جریان هوا به دست آمده است. در رابطه تجربی جدید، چگونگی ارتباط توان اختلاف فشار بخار آب با سرعت جریان هوا نشان داده شده است. نتایج پیش یابی رهیافت جدید توافق مطلوبی را با نتایج انـدازه گیـری نشـان مـی دهد. مقایسه نتایج آهنگ تبخیر از سطح آزاد آب با نتایج آهنگ تبخیر از سطوح خیس شده نشان می دهـد که در سرعتهای پایین هوا، تبخیر از سطوح خیس شده بیش از تبخیر از سطح آزاد آب است و در سـرعتهای بالای حرکت هوا، عکس آن اتفاق می افتد.