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Further development and verification of the model for evaporation from pools

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The author's model for evaporation from water pools is further developed and verified. Further development includes the determination of wind velocity in application to outdoor pools. A value for this height at which wind velocity is to be determined is proposed and verified through analysis of test data. Furthermore, a method for calculating the velocity at this height from measurements at other heights is proposed and verified by analysis of test data. The air velocity above indoor pools is discussed and recommendations are made for the velocity to be used in calculations. The model is further verified with new data that include those for an outdoor swimming pool (there were none before) and data for air at temperatures up to 269 °C, with the maximum temperature in previous data analysis being 200 °C. All data were also compared to 20 other prediction methods. The Shah model had a mean absolute deviation of 15.9% for 537 data points from 29 sources. All others had much larger deviations.

Introduction

Calculation of evaporation from water pools is required in many applications that include indoor and outdoor swimming pools, spent fuel pools of nuclear power plants, water reservoirs, heat rejection pools for processes such as refrigeration systems, and process tanks. Many methods for the calculation have been proposed, including one by the present author. These were discussed and evaluated in Shah (2022). The author's model, Shah (2018), requires the air velocity over the pool. Air velocity over outdoor pools increases with height, being zero at the contact with ground and increasing in the boundary layer with distance from ground. The height at which velocity is to be used and how to determine it were not specified. This matter was investigated during the present research. In indoor pools air velocity varies with height as well as laterally, as has been shown in many studies, for example, the computational fluid dynamics (CFD) study of Li and Heiselberg (2005), and the experimental study by Limane, Fellouah, and Galanis (2017), which was accompanied by CFD simulation. As velocity has a considerable effect on the evaporation predicted and as it varies with location, it is important to specify the location at which it is to be obtained. This article attempts to address this problem.

Many formulas for calculation of evaporation from indoor swimming pools involve air velocity. Air velocity above indoor pools varies considerably along all three axes. None of the formulas specify the location for which the velocity should be used. This topic is discussed and a recommendation is made for the velocity to be used.

Further evaluation and verification of predictive method are always desirable. In Shah (2022), the Shah model and other predictive methods were compared with data from 25 sources. Verification with additional data is presented here. These include data for air at up to 269 °C and relative humidity down to zero. Data previously analyzed were for air temperatures up to 200 °C and minimum relative humidity of 0.21%. Results of comparison of the entire database (data from 29 sources) with 21 prediction methods are presented and discussed. Note that the water temperature mentioned throughout this article is the bulk water temperature.

Previous work

Experimental studies

There have been many experimental studies in which evaporation was measured. Many of them do not provide sufficient details of the parameters needed to analyze them. Typically, such papers present evaporation versus vapor pressure difference without giving the air and water temperatures and relative humidity. Shah (2022) listed 25 studies that provide sufficient details for analyzing them. However, none of them was for an outdoor pool.

A number of studies have been done for which the objective is to develop computer models for predicting energy consumption and water temperature for outdoor

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pools. Examples of such models are Woolley, Harrington, and Modera (2011) and Lovell et al. (2019). In these and other such studies, evaporation rate was not measured and the studies do not provide analyzable data. Smith, Jones, and Lof (1994) measured evaporation from an outdoor pool but they have not provided analyzable data.

The only studies on outdoor pool that provides analyzable data are those of Bernhard et al. (2019a, 2019b). They measured evaporation from a 25 m × 25 m swimming pool, together with air and water temperatures, air relative humidity, and air velocity.

Some experimental studies were found for which the data were not analyzed in Shah (2022). One of them is that of Haji and Chow (1988) for evaporation from a tray at the bottom of a duct in which high temperature dry air was flowing. The temperature of air was up to 269 °C, which considerably exceeds the maximum temperature of 200 °C in the data previously analyzed. Analysis of these data is presented in the third section.

Another new source is Poos and Varju (2019), which provides data for natural convection from a vessel of 0.89 m diameter.

Asdrubali (2009) measured evaporation in a scale model of swimming pools. Tests were done at water temperature 20 to 30 °C, air temperature 2° higher than water temperature, relative humidity 50 to 70%, and air velocity 0.05 to 0.17 m/s. Mass transfer coefficients were obtained from these tests, and using them, predictions were made for full-sized swimming pools at all the conditions under which measurements were done on the scale model. As the Asdrubali paper is widely quoted, it was felt that a comparison of the evaporation predictions in it with various correlations will be interesting to readers.

Song and Chen (2020) performed tests on evaporation from a 30-mm-deep water pool over compacted and saturated soil in an environmental chamber with forced airflow. Air velocity was 0.14 to 0.44 m/s. They fitted a number of correlations to their data but did not compare them to any other correlation. The data are not given in analyzable form.

Aldarabseh and Merati (2021) measured evaporation from a tank flush with the bottom of a wind tunnel. Measurements were done over a wide range of temperatures and air velocities. They compared their data to many correlations and found large deviations. It is not possible to analyze their data, as the conditions (air and water temperatures, relative humidity) for individual data points are not given. Aldarabseh and Merati (2022) used the same apparatus but waves of varying magnitudes were induced into the water surface. They found that waves increased the rate of evaporation compared to that from quiet water surface. Analyzable data have not been provided.

As noted in the preceding, the new analyzable data found during the present work are those of Bernhard et al. (2019a, 2019b), Haji and Chow (1988), Poos and Varju (2019), and Asdrubali (2009) model output.

Methods for predicting evaporation

The most verified method for calculation of evaporation is that of Shah, which is given by the following equations:

$$E_{nc} = 35\rho_w(\rho_\infty - \rho_w)^{1/3}(W_w - W_\infty) \tag{1}$$

$$E_{fc} = 0.00005(p_w - p_\infty)\left(\frac{u}{0.12}\right)^{0.8} \tag{2}$$

Evaporation is the larger of those given by Equations 1 and 2.

Equation 1 is for the evaporation due to natural convection. This was first derived in Shah (1992) by application of the analogy between heat and mass transfer. Equation 2 is for the evaporation due to forced convection. If the air velocity $u < 0.12$ m/s, $u = 0.12$ is used. Thus, the minimum evaporation due to forced convection is

$$E_{fc,\,minm} = 0.00005(p_w - p_\infty) \tag{3}$$

Equation 3 was derived by Shah (2012) through analysis of data when $\rho_w > \rho_\infty$ and there was no forced airflow over pool surface, airflow being caused by building ventilation system, and/or infiltration/exfiltration through cracks in the building envelope. The velocity factor in Equation 2 was arrived at in Shah (2018) by the analysis of test data. Jang et al. (2019) compared this model against data from several sources for which the conditions were similar to those on the water pool for their nuclear reactor. Good agreement was found.

The complete Shah model is given in the Appendix.

Many other formulas for prediction of evaporation have been proposed. Many of them are of the form

$$E = (b + cu^n)(\mathrm{p}_w - p_\infty)^m \tag{4}$$

Values of the constants and exponents in Equation 4 as given in the correlations of various researchers are listed in Table 1. Many formulas have been developed for evaporation from pools and reservoirs; the Meyer (1942) formula listed in Table 1 is one of them. Many other such formulas are listed in Rohwer (1931), Hjelmfelt and Cassidy (1975), Sartori (2000), and Lovell et al. (2019).

All the formulas in Table 1 with the exception of the formula of Smith, Jones, and Lof (1994), which is for an outdoor pool, were compared with data from 25 sources by Shah (2022). The Shah model and the correlations of Hugo (2015), Mancić et al. (2021), and Biasin and Krumme (1974) were also included. Only the Shah model gave good agreement with data. Note that none of the data analyzed were for an outdoor pool.

Jodat, Moghiman, and Anbarsooz (2012) performed tests on evaporation from a pan in a wind tunnel, and fitted the following equations to their data:

For $u \le 0.1$ m s^{-1},

$$E = C\ (p_w - p_\infty)^{1.105}(\rho_\infty - \rho_w)^{0.153} \tag{5}$$

For $0.3 \le u \le 6$ m s^{-1},

$$E = 0.001(0.0362u^3 + 0.01814u^2 + 0.04818u + 0.02264)(p_w - p_\infty)^{0.009u^2 - 0.132u + 1.186} \tag{6}$$

The constant C in Equation 5 is given as 6.9E-4. Its use overpredicted data by an order of magnitude. Changing to $C = 6.9$E-5 gave good agreement with data. It seems that there is a typing error in their paper, but the same value of C is also given in Jodat and Moghiman (2011). The

Table 1. Constants and exponents in the correlations of the form of Equation 4 for evaporation from undisturbed water pools.

Author	b	c	n	m	Basis (notes)
Box (1876)	7.78e-5	0	0	1	
Carrier (1918)	1.33e-4	1.17e-4	1	1	Pool with forced airflow data. $u = 0$ to 6.3 m/s
Himus and Hinchley (1924)	2.58e-5	0	0	1.2	Small vessel in quiet air data
Rohwer (1931)	1.37e-4	8.25e-5	1	1	Wind tunnel tests
Lurie and Michailoff (1936)	1.65e-4	1.26e-4	1	1	Wind tunnel tests. Air temp. 40 to 225 °C, $u = 1$ to 8.5 m/s.
Meyer (1942)	1.56e-4	3.51e-5	1	1	Data for small shallow lakes
Boelter, Gordon, and Griffin (1946)	1.62e-5	0	0	1.22	Small vessel in quiet air data. Conditions in Table 2.
Baturin (1972)	4.72E-5	1.05E-4	1	1	Wind tunnel tests
Smith, Jones, and Lof (1993)	9.84e-5	8.66e-5	1	1	Indoor swimming pool. T_a 24–27 °C, T_w 28 °C, RH 55–61%.
Smith, Jones, and Lof (1994)	9.58e-5	1e-4	1	1	Outdoor swimming pool. $T_w = 28.9$ °C, $T_a =$. 14.4 to 27.8 °C, RH 27–65 %, $u = 0$ to 3 m/s.
VDI (1994)	4e-5	0	1	1	
Hens (2009)	4.086e-5	0	1	1	Outdoor swimming pools. Water temp. 27 to 31 °C.
Inan, Osgur, and Yilmaz (2017)	3.24e-5	9.07e-5	1	0.695	Small vessel in a wind tunnel data. $T_w = 14$ to 24 °C, $T_\infty = 16$ to 26 °C, $u = 0.2$ to 0.38 m/s
ASHRAE (2019)	6.65e-5	5.85e-5	1	1	0.5 × Carrier formula

Note: In the formulas involving latent heat of water, $i_{fg} = 2400$ kJ/kg was used.

correlation with $C = 6.9E\text{-}5$ is henceforth called the modified Jodat et al. correlation.

Song and Chen (2020) fitted several correlations to the data they obtained from the tests described earlier in this section. Among them, they recommended the following formula as the best:

$$E = (0.00092 + 0.0013u)(100 - \phi) \tag{7}$$

where φ is the relative humidity in percent.

Based on their tests described earlier in this section, Aldarabseh and Merati (2021) gave separate empirical correlations for air velocities 0.4–0.5 m s^{-1}, 0.8–2.1 m s^{-1}, and 2.5 m s^{-1}. Because of the discontinuity in the velocity range between their three equations, it is not possible to compare them to all data.

Table 2. Complete range of data that were analyzed.

Parameter	Range
Pool types	Laboratory vessels, swimming pools (unoccupied, indoor and outdoor), spent fuel pools
Pool area, m^2	0.022 to 525
Water temperature, °C	7.1 to 94.2
Air temperature, °C	6.3 to 269
Air relative humidity, %	0 to 98
Air velocity, m/s	0 to 8.5
Number of data sources	29
Number of data points	537
MAD of Shah model, %	15.9

Air velocity over outdoor pools

Lovell et al. (2019) in their study on an outdoor pool measured air velocity at 3 m height and used it in calculating evaporation as a part of their model for the calculation of water temperature and energy requirements. Sartori (2000) noted that various researchers have used velocities at heights ranging from 0.3 to 10 m in their correlations for evaporation from lakes and water reservoirs. In the formulas for lakes and reservoirs given in Hjelmfelt and Cassidy (1975), velocities used are at elevations of 4 to 9 m.

Smith, Jones, and Lof (1994) measured evaporation from an outdoor unoccupied pool. They measured wind velocity at a height of 0.3 m above the water surface, with the instrument located at the edge of the pool. Measured wind velocity ranged from 0.1 to 3.3 m/s. They gave a correlation of their data that had the form of Equation 4; it is included in Table 1. They state that the evaporation predicted by this equation at a velocity of 0.03 m/s was equal to the evaporation measured at the same velocity during their study on an indoor pool, Smith, Jones, and Lof (1993). As shown in the fourth section, the height of 0.3 m was found to be suitable for use in the Shah model.

Many methods for the calculation of velocity at any location and height using the measurements and different locations and heights have been proposed. Some of them are discussed in the following.

According to Hjelmfelt and Cassidy (1975), velocity u at height H above ground may be calculated from the measured velocity u_{ref} at height H_{ref} by the following equation for turbulent boundary layers:

$$\frac{u}{u_{ref}} = \left(\frac{H}{H_{ref}}\right)^{1/7} \tag{8}$$

Table 3. Results of comparison of test data for evaporation from quiet water surfaces with various prediction methods.

		Deviations of correlations, % MAD δ_{avg}																		
Data sources	N	Shah 2018	Box 1876	Carrier 1918	Himus and Hinchley 1924	Rohwer 1931	Lurie and Michailoff 1936	Meyer 1942	Boelter, Gordon, and Griffin 1946	Baturin 1972	Biasin and Krumme 1974	Smith, Jones, and Lof 1993, 1994	VDI 1994	Hens 2009	Mod. Jodat, Moghiman, and Anbarsooz (2012)	Raimundo et al. 2014	Hugo 2015	Inan, Osgur, and Yilmaz 2017	ASHRAE 2019	Song and Chen (2020)
Haji and Chow (1988)	32	9.0	82.3	25.3	62.4	37.6	14.9	51.1	71.6	49.6	63.3	40.4	90.9	90.7	33.2	8.0	24.9	67.8	62.7	93.2
		–7.3	–82.3	–25.3	–62.4	–37.6	–14.9	–51.1	–71.6	–49.6	–83.3	–40.4	–90.9	–90.7	–33.2	–4.9	–24.9	–67.8	–62.7	–93.3
Poos and Varju (2019)	1	17.0	8.0	115.9	43.5	107.7	155.3	124.2	3.5	12.5	69.6	53.6	44.5	43.3	33.9	19.6	48.2	0.3	4.9	14.0
		–17.0	8.0	115.9	43.5	107.7	155.3	124.2	3.5	–12.5	–69.6	53.6	–44.5	–43.3	33.9	–19.6	48.2	–0.3	4.9	14.0
Bernhard et al. (2019a)	5	4.2	68.8	5.6	53.3	15.4	11.3	24.7	65.9	43.5	81.3	25.8	83.9	83.6	25.0	7.7	19.4	41.1	52.2	88.6
		–4.2	–68.8	–4.5	–53.3	–15.4	11.3	–24.7	–65.9	–43.5	–81.3	–25.8	–83.9	–83.6	–25.0	–7.7	–19.4	–41.1	–52.2	–88.6
Bernhard et al. (2019b)	4	12.8	60.7	13.8	42.6	8.6	33.1	10.5	58.2	34.7	78.4	12.1	79.8	79.3	13.5	3.9	5.4	29.8	43.1	87.3
		12.8	–60.7	13.8	–42.6	1.9	33.1	7.1	–58.2	–34.7	–78.4	–12.1	–79.8	–79.3	–13.5	3.9	–5.4	–29.8	–43.1	–87.3
Asdrubali (2009)*	98	18.1	20.1	115.9	53.6	116.8	164.3	138.8	19.8	15.8	77.9	46.9	40.1	38.8	27.4	32.8	61.7	13.5	15.0	37.4
		–17.1	16.5	115.9	53.6	116.8	164.3	138.8	10.7	–14.9	–77.9	–46.9	–40.1	–38.8	–3.1	–32.8	61.7	–2.8	8.0	–36.7
Previously analyzed data	397	16.1	47.6	66.9	48.4	69.2	96.5	84.7	36.5	39.0	94.8	44.3	61.8	61.2	23.0	40.2	38.7	46.5	40.0	69.4
		–1.3	–20.8	56.7	14.1	64.4	90.3	65.3	–16.2	–33.3	–94.4	19.0	–59.3	–58.4	23.0	–33.8	36.2	–29.4	–21.7	–52.3
All data	537	15.9	44.9	72.5	50.2	75.2	102.2	91.6	35.9	35.3	90.7	46.0	59.9	59.2	24.4	36.4	41.6	41.5	36.9	65.2
		–4.5	–18.3	61.8	15.7	59.3	96.6	70.5	–15.8	–31.0	–90.5	21.8	–58.0	–57.1	24.4	–31.4	29.0	–26.9	–19.1	–52.3

*The data used are predictions of Asdrubali's model based on his tests on a scale model.

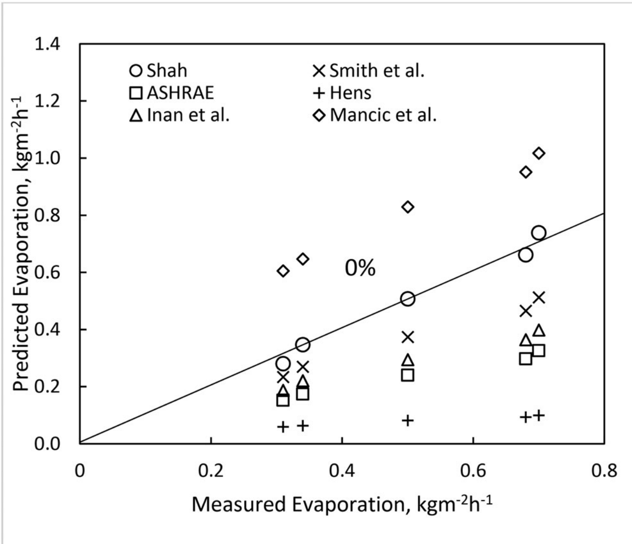

Figure 1. Comparison of the data of Bernhard et al. (2019a) for evaporation from an outdoor swimming pool with some correlations.

According to Australian standard AS 3634 (1989), the velocity u to be used for calculation of outdoor swimming pools is to be calculated from the velocity u_{BOM} reported by the Bureau of Meteorology by the following formula:

$$u = 0.15u_{BOM} \tag{9}$$

The Bureau of Meteorology measures wind speed at 10 m above ground. The velocity given by this formula is lower than will be predicted by Equation 8 even at 1 mm above ground.

Delgado et al. (2016) discuss the variation of wind speed with height. They note that one of the methods to relate the speeds at different heights is

$$\frac{u_1}{u_2} = \left(\frac{H_1}{H_2}\right)^n \tag{10}$$

The exponent n depends on the territory, with its value ranging from 0.1 for open water to 0.43 for evergreen forest. There are many other methods for scaling velocity. Some of them have been described in Delgado et al. (2016) and Lovell et al. (2019).

Data analysis

The new test data together with the data analyzed in Shah (2022) were compared to the correlations discussed in the preceding section. The new data are those of the Bernhard et al. (2019a, 2019b), Haji and Chow (1988), Poos and Varju (2019), and Asdrubali (2009) models.

The complete range of data analyzed is listed in Table 2. In applying the modified Jodat et al. correlation, Equation 6 was used for $u > 0.1$ m/s; when $\Delta\rho < 0$, $\Delta\rho = 0$ was inserted in Equation 5. Where air velocity above pool during natural convection tests was not reported, $u = 0.075$ m/s was inserted in the formulas involving velocity for reasons discussed in the fourth section.

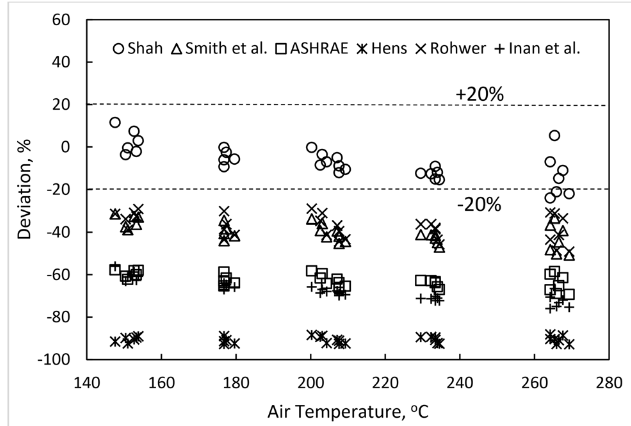

Figure 2. Comparison of the data of Haji and Chow (1988) for evaporation into high temperature air with some correlations.

Deviations of correlation predictions from data are defined as follows:

$$Deviation = (E_{predicted} - E_{measured})/E_{measured} \tag{11}$$

Mean absolute deviation (MAD) is defined as

$$MAD = \frac{1}{N}\sum_{1}^{N}\left|(E_{predicted} - E_{measured})/E_{measured}\right| \tag{12}$$

Average deviation is defined as

$$\delta_{avg} = \frac{1}{N}\sum_{1}^{N}\left\{(\mathrm{E_{predicted}} - \mathrm{E_{measured}})/\mathrm{E_{measured}}\right\} \tag{13}$$

The results of comparison of all data with all correlations except that of Mancić et al. are given in Table 3. The Mancić et al. correlation gave very large deviations with most data. Those for the new data are given separately for each source, while the results for the data that were also analyzed in Shah (2022) are combined together in one row. The Shah model is seen to give the best agreement with all data. The results and some other related topics are discussed in the next section.

Discussion

Outdoor pool

As noted in the second section, the only analyzable dataset found for outdoor pools is that of Bernhard et al. (2019a, 2019b). The pool was 25 m × 25 m. The air temperature was 17.2–19.8 °C, relative humidity 63–82%, and water temperature 25.8–29.1 °C. Wind velocity was measured at a height of 3 m at the same site and was 0.9 to 1.49 m/s. As Smith, Jones, and Lof (1994) in their tests on an outdoor pool had measured wind velocity at 0.3 m height and used it in their correlation of their data, it was decided to try using the velocity at that height. Velocity at 0.3 m height was calculated from the velocity at 3 m height using the boundary layer formula, Equation 8. The data were then compared to the Shah model, as well as to other formulas. Figure 1

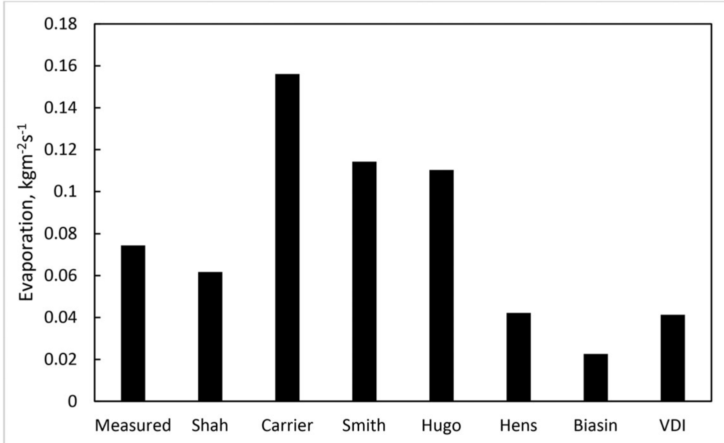

Figure 3. Comparison of the evaporation rate measured by Poos and Varju (2019) with predictions of some correlations.

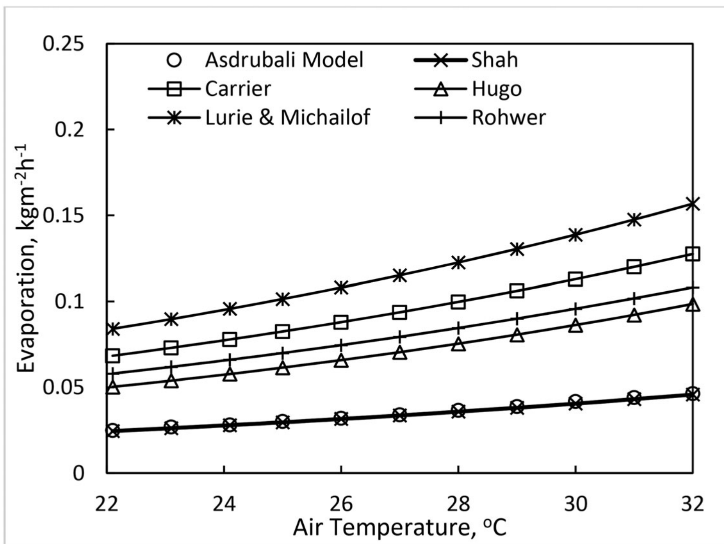

Figure 4. Comparison of the predictions of Asdrubali (2009) model for evaporation from a pool with those of various correlations. Water temperature 2 °C lower than air temperature, relative humidity 70%, air velocity 0.05 m/s.

shows the comparison of these data with various correlations. It is seen that the Shah model is in close agreement with the data; the MAD was 4.2%. This supports the use of the velocity at 0.3 m height and use of Equation 8 for calculating the velocity from measurements at another height, at least if the velocity is measured at the same site. Data on evaporation from different sites are needed to determine whether the choice of 0.3 m height and use of Equation 8 to scale wind velocity works for them or whether different strategies are needed.

High air temperature data of Haji and Chow

In the tests of Haji and Chow (1988), a vessel 305 mm long and 50.8 mm wide was attached to the bottom of a duct. Dry air flowed through the duct. Air temperatures ranged from 147 to 269 °C and water temperatures from 39 to 51 °C. Air humidity was 0 and air velocity was 1.2 to 2.3 m/s. Figure 2 shows the deviations of some prediction methods from the measured evaporation rates. It is seen that the Shah model predicts the data within ±20%. The MAD of the Shah model with these data is 9%. The maximum air temperature in the data analyzed by Shah (2022) was 200 °C. The good agreement with these data extends the verified range of the Shah model up to 269 °C air temperature.

Note that Haji and Chow found that their data did not agree with the theory of Chow and Chung (1983). They attempted to adjust the data so as to make them agree with the Chow and Chung theory. The data shown in Figure 2 are their measured data, not the adjusted data. The agreement of their measurements with the Shah model, which has been validated with data from numerous sources, including those at high air temperatures, indicates that the deficiency was in the theory of Chow and Chung, not in the Haji and Chow measurements.

Data of Poos and Varju (2019)

Poos and Varju (2019) measured evaporation from a vessel of 0.89 m diameter under conditions of natural convection. Air temperature was 20.4 °C, relative humidity was 23.6%,

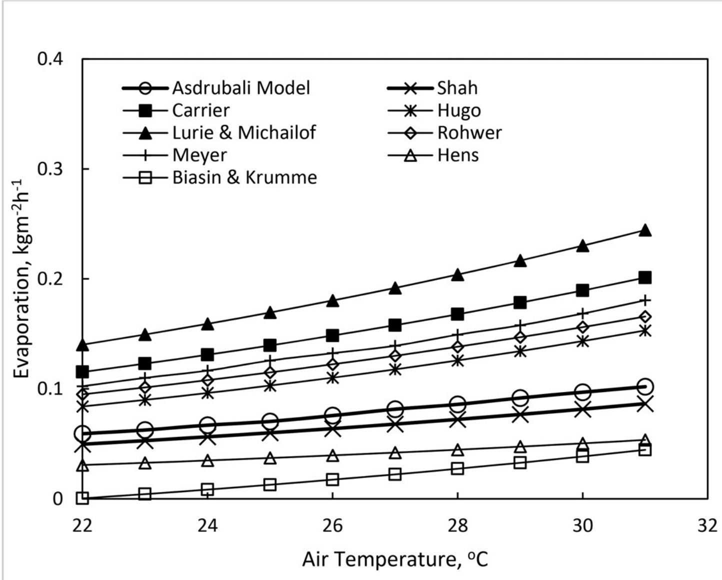

Figure 5. Comparison of the predictions of Asdrubali (2009) model for evaporation from a pool with those of various correlations. Water temperature 2 °C lower than air temperature, relative humidity 60%, air velocity 0.17 m/s.

and water temperature was 14 °C. Air velocity above the tank was measured to be 0.15 m/s; the height of the measurement location was not stated but it was directly above the vessel. The tests continued for 120 h, during which evaporation rate remained constant. Figure 3 shows the comparison of their measured evaporation with several prediction methods. It is seen that the Shah model predicts fairly close to the measured evaporation, while the others in that figure predict considerably higher or lower.

Comparison with the model of Asdrubali

These were compared to the Shah model as well as other correlations. Figure 4 shows the comparison of Asdrubali predictions for air velocity of 0.04 m s^{-1} with those of various correlations. It is seen that the Shah model predictions are very close to it, while others have large differences with it. Figure 5 shows the comparison with Asdrubali predictions for air velocity of 0.17 m s^{-1}. The Shah model predictions are about 15% lower than this.

Air velocity above indoor pools

Some of the formulas for the calculation of evaporation from indoor pools require the insertion of air velocity over the pool. Hence the determination of this velocity needs some discussion.

In swimming pools, airflow over the pool is due to the building ventilation systems. Typically, air is discharged over the deck on one side of the pool and returned through openings above the deck on the other side of the pool. Li and Heiselberg (2005) performed CFD simulation of a large swimming pool. Air velocity was found to vary considerably along the three axes. Within half a meter of the water surface, air velocity typically varied between near zero and about 0.15 m s^{-1}.

Limane, Fellouah, and Galanis (2017) performed CFD analysis of a large swimming pool and also did measurements of velocity at 0. 2 and 3.25 m above the water surface. The measured velocity at 0.2 m height ranged from near zero to 0.1 m/s except for one data point at 0.2 m/s.

Smith, Jones, and Lof (1993) measured air velocity over the middle of a large indoor swimming pool using neutral-buoyancy balloons. With the building ventilation system operating, the air velocity was found to be 0.035 to 0.05 m/s. The ASHRAE Handbook (2019) in its simplification of the Carrier formula considered air velocity to be 0.05 to 0.15 m/s. Based on this information, it is suggested to use 0.15 m/s velocity to obtain the upper limit of evaporation. For the most likely estimate of evaporation, use of 0.075 m/s velocity is suggested.

Accuracy of various prediction methods

Shah (2022) defined the following three regimes of evaporation.

1. Natural convection dominant regime, in which both natural convection and forced convection are possible but the resulting evaporation is due to the natural convection mechanism. This occurs when $\rho\infty > \rho w$ and Enc > Efc. Equation 1 gives the resulting evaporation.
2. Forced convection dominant regime, in which both natural convection and forced convection are possible but the resulting evaporation is due to the forced convection mechanism. This occurs when $\rho\infty > \rho w$ and Efc > Enc. Equation 2 gives the resulting evaporation.
3. Forced convection only regime, in which natural convection is not possible as $\rho\infty \le \rho w$. Evaporation is calculated by Equation 2.

Table 4 gives the deviations of some of the correlations in these three regimes. The correlations chosen are those

Table 4. Deviations of some correlations in the three regimes of evaporation.

Condition	N	Deviations of correlations, % MAD Average									
		Shah 2018	Carrier 1918	Boelter, Gordon, and Griffin 1946	Baturin 1972	Smith, Jones, and Lof 1993	VDI 1994	Modified Jodat, Moghiman, and Anbarsooz (2012)	Raimundo et al. 2014	Hugo 2015	ASHRAE 2019
Natural convection dominant: $E_{nc} > E_{fc}$ with ($\rho_w < \rho_\infty$)	184	13.7	64.6	18.9	43.2	35.1	55.8	17.1	49.5	30.8	34.0
		−2.5	60.4	2.0	−41.9	16.3	−55.5	17.1	−45.1	25.3	−22.7
Forced convection dominant: $E_{nc} > E_{fc}$ with ($\rho_w < \rho_\infty$)	219	17.0	93.4	38.3	28.8	55.3	55.7	22.8	21.6	53.3	36.4
		−4.2	90.2	−10.6	−20.3	40.2	−51.4	22.8	−15.1	43.6	−4.9
Forced convection only: ($\rho_w > \rho_\infty$)	134	17.1	59.8	55.2	35.2	46.0	72.4	36.9	23.7	37.4	44.1
		−7.6	30.5	−48.6	−33.6	−0.6	−72.2	36.9	−7.3	10.4	−34.8
All regimes	537	15.9	72.5	35.9	35.3	46.0	59.9	24.4	36.4	36.4	36.9
		−4.5	61.8	−15.8	−31.0	21.8	−58.0	24.4	−31.4	−31.4	−19.1

that are widely used or give reasonable agreement with data in at least one of the regimes. It is seen that the Shah model is the only one that gives good agreement with data in all three regimes and its MAD is lower than that of all others in all regimes. The modified Jodat et al. correlation gives the next best agreement with data in the natural convection dominant regime and the forced convection dominant regime. The Boelter, Gordon, and Griffin (1946) correlation gives good agreement with data in the natural convection dominant regime. The correlation of Raimundo et al. (2014) gives reasonably good agreement with the data in the forced convection dominant and forced convection only regimes. The widely used correlations of Carrier, Smith et al., VDI, and ASHRAE give poor performance in all regimes. The performance of other correlations is also poor.

Recommendations for use in design and analysis

The Shah (2018) model gives good agreement and least deviations with data in all the three regimes. It is therefore the first choice for design and analysis for all regimes. The next best alternatives are:

- Natural convection dominant regime, modified Jodat, Moghiman, and Anbarsooz (2012) and Boelter, Gordon, and Griffin (1946) correlations.
- Forced convection dominant regime, modified Jodat, Moghiman, and Anbarsooz (2012) and Raimundo et al. (2014) correlations.
- Forced convection only regime, correlation of Raimundo et al. (2014)

Conclusion

1. Additional data were collected beyond those analyzed in the author's previous studies. The new data included conditions outside the previous range. These included data from an outdoor swimming pool; no such data were found earlier.
2. Data from 29 studies were compared to 21 methods for prediction of evaporation. These included air temperatures from 6 to 269 °C, relative humidity 0 to 98%, water temperature 7 to 94 °C, and air velocity from near zero to 8.5 m/s. The test data were obtained on laboratory-sized vessels, indoor and outdoor swimming pools, and spent fuel pools of nuclear power plants. The Shah model gave the best agreement in all three evaporation regimes, with the mean absolute deviation for all 537 data points being 15.9%. Only three other correlations gave reasonable predictions in one or two of the evaporation regimes, and none in all three regimes.
3. The choice of height at which wind velocity should be determined in the Shah model and how it should be calculated from measurements at other locations was evaluated through literature review and data analysis. Based on the analysis of the limited data available for outdoor swimming pools, it is recommended that investigations use wind velocity at 0.3 m height and scale the velocity at other heights by the turbulent

boundary layer equation. As data for only one outdoor pool were analyzed, data from more studies are needed.
4. The choice of air velocity in indoor swimming pools was investigated. Recommendations are made for the velocity to be used in evaporation formulas.

Nomenclature

A = area of pool surface, m^2
D = coefficient of molecular diffusion, m^2h^{-1}
E = total evaporation from pools, kg/m^2h
E_{fc} = evaporation due to forced convection, kg/m^2h
$E_{fc,minm}$ = rate of evaporation due to forced convection when $u \leq 0.12$ m/s, kg/m^2h
E_{nc} = evaporation due to natural convection, kg/m^2h
Gr = Grashof number, —
H = height above ground, m
h_M = mass transfer coefficient, mh^{-1}
L = length of pool, m
i_{fg} = latent heat of vaporization of water, kJ/kg
N = number of data points
Pr = Prandtl number, —
p = partial pressure of water vapor in air, Pa
Δp = $(p_w - p_\infty)$, Pa
Sc = Schmidt number $\mu\rho^{-1}$ D^{-1}, —
Sh = Sherwood number h_M DL^{-1}, —
u = air velocity, m/s
W = specific humidity of air, kg of moisture/kg of moist air
μ = dynamic viscosity of air, kg m^{-1} h^{-1}
$\Delta\rho$ = $(\rho_\infty - \rho_w)$, density of air, mass of dry air per unit volume of moist air, kg/m^3 (this is the density used in psychrometric charts and tables)

Subscripts

H = heat transfer
M = mass transfer
w = saturated at water temperature
∞ = away from the water surface

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Appendix

The derivation of the Shah model equations is described in the following.

The physical model used by Shah is as follows. A very thin layer of air that is in contact with water quickly gets saturated due to molecular movement at the air–water interface. If there is no air movement at all, further evaporation proceeds entirely by molecular diffusion, which is a very slow process. If there is air movement, this thin layer of saturated air is carried away by air and is replaced by the comparatively dry room air and evaporation proceeds rapidly. Thus, for any significant amount of evaporation to occur, air movement is essential. Air movement can occur due to the following mechanisms:

1. Air currents caused by natural convection (buoyancy effect). Room air in contact with the water surface gets saturated and thus becomes lighter compared to the room air, and moves upward. The heavier and drier room air moves downward to replace it.
2. For indoor pools, air currents caused by the building ventilation system or infiltration/exfiltration.
3. For outdoor pools, airflow by wind.

The rate of evaporation is given by the relation

$$E = h_M \rho_w (W_w - W_\infty) \tag{A1}$$

where W is the specific humidity of air, the mass of moisture divided by the mass of dry air. The air density ρ is evaluated at the water surface temperature, as recommended by Kusuda (1965).

For natural convection, the pool is modeled as a horizontal heated plate facing upward. Heat transfer during turbulent natural convection to a heated plate facing upward is given by the following relation (McAdams 1954):

$$Nu = 0.14(Gr_H Pr)^{1/3} \tag{A2}$$

Using the analogy between heat and mass transfer, the corresponding mass transfer relation is

$$Sh = 0.14(Gr_M Sc)^{1/3} \tag{A3}$$

where Sc is the Schmidt number. Equations A2 and A3 are for turbulent conditions. Analysis of wide-ranging data for pools showed (Gr_M Sc) to be greater than 2×10^7 and hence in the turbulent range. Hence the use of these equations is appropriate.

Gr_M is defined as

$$Gr_M = \frac{\gamma g (W_w - W_\infty) L^3 \rho^2}{\mu^2} \tag{A4}$$

where

$$\gamma = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial W}\right) \tag{A5}$$

Equation A5 is approximated as

$$\gamma = \frac{\rho_\infty - \rho_w}{\rho(W_w - W_\infty)} \tag{A6}$$

Substituting γ from Equation A6 into Equation A4,

$$Gr_M = \frac{g(\rho_\infty - \rho_w) L^3 \rho^2}{\mu^2} \tag{A7}$$

Substituting Gr_M from Equation A7 into Equation A3 and expanding Sc and Sh,

$$\frac{h_M L}{D} = 0.14\left[\frac{(\rho_\infty - \rho_w) g L^3}{\mu D}\right]^{1/3} \quad \text{(A8)}$$

where D is the coefficient of molecular diffusion. Substituting h_M from Equation A8 into Equation A1,

$$E = (0.14 g^{1/3} D^{2/3} \mu^{-1/3}) \rho_w (\rho_\infty - \rho_w)^{1/3} (W_w - W_\infty) \quad \text{(A9)}$$

The value of $(D^{2/3}\ \mu^{-1/3})$ does not vary much over the typical range of room air conditions. Inserting a mean value, Equation A9 becomes

$$E = 35 \rho_w (\rho_\infty - \rho_w)^{1/3} (W_w - W_\infty) \quad \text{(A10)}$$

This derivation was first given in Shah (1992).

When density of air at the water surface is higher than the density of room air, natural convection essentially ceases and air movement needed to remove saturated air from water surface is entirely due to the air currents caused by building ventilation system or infiltration/exfiltration. By analyzing data for $\rho_r < \rho_w$, Shah (2012) obtained the following formula for evaporation due to these air currents:

$$E = 0.00005\ (p_w - p_r) \quad \text{(A11)}$$

Evaporation is the higher of those predicted by Equation A10 and A11. These equations apply in the absence of forced convection. For forced convection, Equation A11 was modified to the following form by comparison with test data:

$$E_{fc} = 0.00005 (p_w - p_\infty) \left(\frac{u}{0.12}\right)^{0.8} \quad \text{(A12)}$$