An analysis of heat losses from an all-year outdoor swimming pool

Analiza strat ciepła z całorocznego basenu odkrytego

MICHAŁ POMORSKI, ZUZANNA KOŁODKO

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This paper presents an analysis of the amount of the energy needed to maintain a constant temperature in an outdoor swimming pool. The analysis was carried out using real meteorological data in the area which is rich in geothermal water that could compensate losses of heat. Calculations for 5 different temperature of water were made. Losses due to evaporation, convection, radiation processes and solar radiation gains were considered. It was determined that the evaporation process has the highest contribution to general heat loss (about 70%). The radiation process has the lowest impact on heat loss (about 8%). The convection and radiation losses were found to have a linear growth rate with the temperature of water. The evaporation loss is considered to have an exponential growth rate with water temperature, which equals exponential growth rate of the amount of the energy needed to maintain a constant temperature of water.
Keywords: energy balance of an outdoor swimming pool, evaporation loss, solar radiation gain

W pracy przedstawiono analizę całorocznych nakładów energetycznych związanych z utrzymaniem stałej temperatury w basenach odkrytych. Analizę wykonano dla rzeczywistych danych meteorologicznych miejscowości, posiadającej potencjał wód geotermalnych, które mogłyby służyć do pokrywania strat ciepła. Obliczenia wykonano dla 5 poziomów temperatury wody i określono jej wpływ na straty parowania, konwekcyjne i radiacyjne, a także zyski ciepła od promieniowania słonecznego. Określono, że największy wpływ na straty ciepła, wynoszące ok. 70%, ma strata spowodowana parowaniem wody, a najmniejszy (ok. 8%) strata radiacyjna. Dodatkowo zaobserwowano, że strata konwekcyjna i radiacyjna rosną wraz z temperaturą wody w sposób liniowy, natomiast strata parowania w sposób wykładniczy, co przekłada się na wzrost nakładów energetycznych na utrzymywanie stałej temperatury wody wraz z jej wzrostem w sposób wykładniczy.
Słowa kluczowe: bilans energii basenu odkrytego, strata parowania, zyski promieniowania słonecznego

Nomenclature

- a – coefficient of gravitational movement of the surrounding air, –
- a – coefficient of absorption, –
- A – surface area, m^2
- C – technical constant of a black body, W/m^2K^4
- c_p – specific heat capacity, J/kgK
- h – specific enthalpy, J/kg
- h_{evap} – heat of evaporation, J/kg
- I – amount of solar radiation energy per month, Wh/m^2mth
- $\dot{m}$ – mass flow rate, kg/s
- Nd – number of days in a month,
- p – pressure, Pa
- $\dot{q}$ – heat flux density, W/m^2
- $\dot{Q}$ – heat flux, W
- T – temperature, K
- v – wind velocity, m/s

Greek

- α – convective heat transfer coefficient, W/m^2K
- ε – emmisivity, –
- σ – mass transfer coefficient during the evaporation process, kg/sm^2Pa
- φ – air humidity, %

Subscripts

- amb – ambient
- conv – convection
- evap – evaporation
- N0 – horizontal surface
- rad – radiation
- s – saturation conditions
- sky – sky
- sol – solar
- tw – wet bulb thermometer
- vap – vapour
- w – water
- ws – water surface

Introduction

Nowadays, the society places a premium on a healthy lifestyle. More and more people want to visit and enjoy sport and recreation facilities. The growth of interests includes all-year outdoor swimming pools, especially popular are the ones with geothermal water. Most local government units (counties) have a swimming pool baths, but some of them are not suitable for year-round purposes or remain unused. This is largely due to the problem of water heating under low ambient tem-

PhD. Michał Pomorski https://orcid.org/0000-0003-4939-1017 – Department of Thermodynamics and Renewable Energy Sources, Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology, michal.pomorski@pwr.edu.pl
Zuzanna Kołodko – Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology
Correspondence Author – PhD. Michał Pomorski – michal.pomorski@pwr.edu.pl

perature conditions. The most optimal temperature for bathing is 26-28 °C. In sports and swimming pools, the optimal temperature should be 20-22 °C. Water temperature in a recreational pool that is comfortable for human ranges from 28 to even 30 Celsius degrees, while in pools intended for physiotherapy, the water temperature should be even higher than 32 °C. It is related to the need to constantly heat the water in order to maintain a constant, comfortable temperature [4] [6]. With increased heat loss to the environment at low outside air temperatures, considerable energy expenditure is required to keep the water temperature constant, making this a very costly project. The solution limiting the demand for energy is limiting losses through the use of appropriate thermal insulation, the use of swimming pool covers when they are not in use and the selection of an appropriate, efficient and cheap source of energy, e.g. heat from geothermal sources with the use of heat pumps.

Thermal analysis of an outdoor pool

Constant heat and mass exchange in an outdoor swimming pool is a really difficult and complex thermodynamic process. This phenomenon depends on time and many parameters, including temperature of environment, wind velocity, sky temperature and solar radiation. Main processes impacting on heat exchange are presented below:

- loss of heat due to water evaporation,
- loss of heat due to convection,
- loss of heat due to radiation,
- gain of heat due to solar radiation.

Another processes impacting on thermal analysis are:

- heat exchange with the ground,
- heat and mass exchange due to precipitation,
- thermal processes connected to the presence and activity of people (heat gain due to heat exchange generated in a human body and losses of heat due to disturbance of water surface have an impact on increased water evaporation and higher heat transfer coefficient. It equals to a higher losses due to convection).

Water and energy losses need to be filled in by delivering heat and fresh water to the pool. Processes of heat and mass exchange occurring in an outdoor pool are shown in Fig.1.

Calculation of heat transfer to the ground was not included in this paper, as it has a non-significant impact on the heat losses [6]. In addition, thermal effect connected to human activity and precipitation were also not included. All these factors have a negligible impact on the analysis.

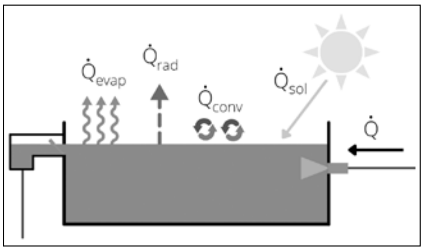


Fig.1.
Scheme of processes of heat and mass exchange occurring in an outdoor pool
Rys. 1. Schemat procesów wymiany ciepła i masy zachodzących w basenie odkrytym

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} - \dot{Q}_{sol}$$

where:

$\dot{Q}$ – heat flux needed to maintain a constant temperature of water, W
$\dot{Q}_{conv}$ – heat flux due to convection loss, W
$\dot{Q}_{rad}$ – heat flux due to radiation loss, W
$\dot{Q}_{evap}$ – heat flux due to water evaporation loss, W
$\dot{Q}_{sol}$ – heat flux due to solar radiation gain, W

The analysed heat fluxes are referred to a water surface unit.

Heat loss due to convection

Heat exchange by convection between water surface and surrounding air was determined by using formula coming from Newton's Law. According to the Newton's Law heat flux density is defined by a formula:

$$\dot{q}_{conv} = \alpha \cdot (T_{ws} - T_{amb})$$

where:

α – convective heat transfer coefficient, W/m^2K
T_{ws} – temperature of water surface, K
T_{amb} – temperature of ambient, K

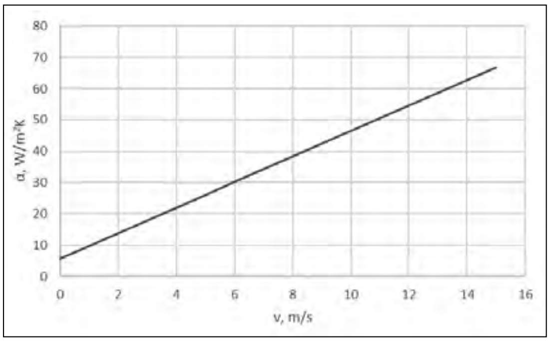
Most challenging in the formula presented above is how to define heat transfer coefficient and water surface temperature. Heat transfer coefficient value depends on the type of convection above the water surface. In an outdoor swimming pool flow of air due to wind has a significant impact (a forced convection). Heat transfer coefficient value was defined using the formula presented in [1]. It defines the coefficient using linear dependence on wind speed. Speed of wind is based on meteorological data from the analysed location:

$$\alpha = 5{,}7 + 4{,}07 \cdot v$$

where:

v – wind velocity, m/s

Fig. 2.
The dependence of the convective heat transfer coefficient as a function of wind velocity
Rys. 2. Zależność konwekcyjnego współczynnika przejmowania ciepła w funkcji prędkości wiatru



Heat transfer by convection occurs between water surface and surrounding air. Temperature of water surface is different from estimated temperature of water in the pool. This temperature can be approximated basing on estimated temperature of water in the pool and wet bulb thermometer temperature [1]:

$$T_{ws} = T_w - 0{,}125 \cdot (T_w - T_{tw})$$

where:

T_w – water temperature, K
T_{tw} – wet bulb thermometer temperature, K

Temperature of wet bulb thermometer depends on temperature of dry bulb thermometer and relative humidity of air. It was adopted from psychrometric tables.

Heat loss due to radiation

Radiation heat loss due to infrared radiation is calculated using the formula presented in [3]:

$$\dot{q}_{rad} = \varepsilon_{ws-sky} \cdot C \cdot \left[\left(\frac{T_{ws}}{100} \right)^4 - \left(\frac{T_{sky}}{100} \right)^4 \right]$$

where:

ε_{ws-sky} – substitutive emissivity between water surface and sky
C – technical constant of a black body (C = 5,67 W/m^2K^4)
T_{sky} – sky temperature, K

Substitutive emissivity was defined using Christiansen's formula [3]:

$$\varepsilon_{ws-n} = \frac{1}{\frac{1}{\varepsilon_{ws}} + \frac{A_{ws}}{A_{sky}} \cdot \left(\frac{1}{\varepsilon_{sky}} - 1 \right)}$$

where:
ε_{ws} – emissivity of water surface
ε_{sky} – emissivity of sky
A_{ws} – water surface area, m^2
A_{sky} – sky surface, m^2

Due to the fact that there is a relation between the water surface area and the surrounding air:

$$A_{ws} \ll A_{sky}$$

then the substitutive emissivity will be equal to the water surface emissivity:

$$\varepsilon_{ws-sky} = \varepsilon_{ws}$$

For the analyses, based on the literature data, the emissivity value of the water surface was assumed to be $\varepsilon_{ws} = 0{,}95$ [9].

Heat loss due to water evaporation

The heat loss flux density, which is carried away from the water surface by evaporation, was determined from the relation [5]:

$$\dot{q}_{evap} = \dot{m}_{vap} \cdot h_{vap}(T_{ws})$$

where:
$\dot{m}_{vap}$ – vapour mass flow per unit, kg/sm^2
$i_{vap}(T_{ws})$ – specific enthalpy of water vapour, J/kg

One of the most difficult issues is the determination of the vapour mass flux evaporating from the water surface. There are many formulas in the literature to determine this parameter [10] [11]. The value of the evaporating water flux depends, among others, on disturbance of the water surface. During the time when the swimming pool is in use, the mass flux of generated vapour will be greater as a result of disturbing the water surface by the pool users than during the periods when it is not used. In this work, the vapour mass flux evaporating from the water surface, which is dependent on the difference in the partial pressure of water vapour in the water-air boundary layer and on the air pressure, was determined from the Dalton formula based on the dependence described in [1]:

$$\dot{m}_{vap} = \sigma \cdot \left[p_s(T_{ws}) - p_{vap}(T_{amb}) \right] \cdot \frac{1000}{p_{amb}}$$

where:
σ – mass transfer coefficient in the evaporation process, kg/sm^{2}Pa
$p_s(T_{ws})$ – partial pressure of water vapour in the water-air boundary layer, equal to the saturation pressure for the temperature T_{ws}, Pa
$p_{vap}(T_{amb})$ – partial pressure of water vapour contained in the air, Pa
p_{amb} – ambient pressure, hPa

The value of the mass transfer coefficient during evaporation was determined from the empirical relation presented in [1]:

$$\sigma = 2{,}1 \cdot 10^{-6} \cdot (a + 0{,}017 \cdot v)$$

where:
a – coefficient taking into account the gravitational movement of the surrounding air, depending on the temperature of the water and air surface (for the water surface temperature up to 30 °C – a = 0,022; for the water surface temperature 40 °C – a = 0,028) [2]

The enthalpy of the vapour was defined as the sum of the enthalpy of water evaporation and the enthalpy of water vapour for the water surface temperature:

$$h_{vap}(T_{ws}) = h_{evap}(T_{ws}) + c_{pvap} \cdot T_{ws}$$

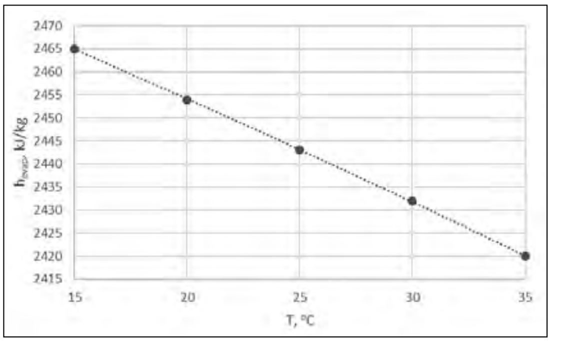
where:
h_{evap} – heat of water vaporization process, kJ/kg
c_{pvap} – specific heat at constant pressure for water vapour, kJ/kgK

The heat of vaporization was assumed as a dependence on the water surface temperature:

$$h_{evap}(T_{ws}) = -0{,}0057 \cdot T_{ws}^2 - 1{,}9543 \cdot T_{ws} + 24{,}95{,}5$$

In the analysed range of water temperature, the heat of vaporization changes with the temperature change almost linear (Fig. 3).

Fig. 3.
The dependence of the heat of evaporation of water in the function of temperature
Rys. 3. Zależność ciepła parowania wody w funkcji temperatury



Heat gain from solar radiation

The density of the heat gain flux from solar radiation was determined on the basis of the monthly sum of solar radiation energy reaching the water surface:

$$\dot{q}_{sol} = \frac{I_{N0}}{Nd \cdot 24} \cdot a$$

where:
I_{N0} – monthly sum of solar radiation energy on the horizontal surface, Wh/m^{2}mth
Nd – number of days in the month
a – solar radiation absorption coefficient

The solar radiation energy absorption coefficient by water was assumed to be a = 0.85 based on the literature data [9].

Results

The analyzes were carried out on the basis of the actual monthly average meteorological data for the town where there is a potential for the use of thermal waters (Lądek Zdrój). The most important climatic data are presented in Table 1 and Figures 4 and 5.

Tab. 1. Meteorological data for Lądek Zdrój [12][13][14]
Tab. 1. Dane meteorologiczne dla miejscowości Lądek Zdrój [12][13][14]

month	T_{amb}	T_n*	φ	v	I_{N0}
	°C	°C	%	km/h	Wh/m^2
January	-3,3	-10,7	86	20	30471
February	-2,3	-11,2	85	20	37591
March	1,2	-4,6	80	19	72778
April	6,9	-1,7	71	15	103419
May	11,7	5,3	72	13	148185
June	15,1	7,5	73	12	145962
July	16,9	9,7	73	11	147502
August	16,7	8,8	73	11	122824
September	12,3	4,2	78	13	82274
October	7,7	-0,4	84	14	52272
November	3,3	-6,8	87	16	27445
December	-1,5	-10,6	87	19	23686

the temperature of the sky was assumed for the nearest weather station (Kłodzko)

The analyses were performed for 5 levels of water temperature: 20 °C, 24 °C, 27 °C, 29 °C and 33 °C, which correspond to the water temperature in pools for various purposes.

As a result of the conducted analyses, the distribution of the heat loss flux density

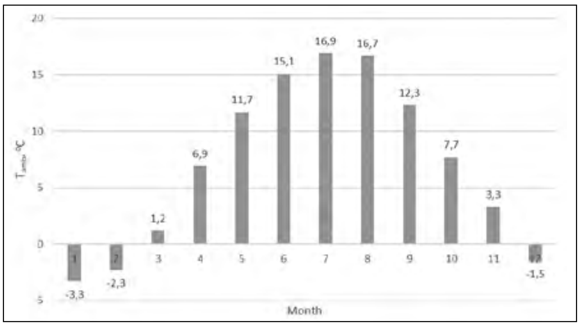
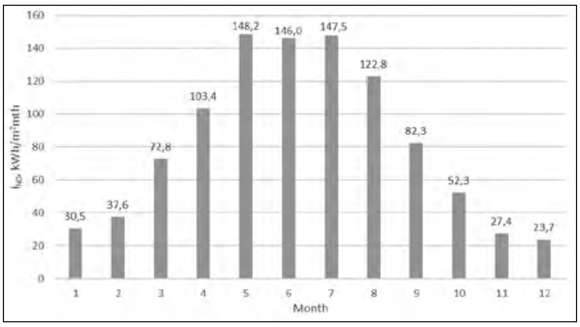


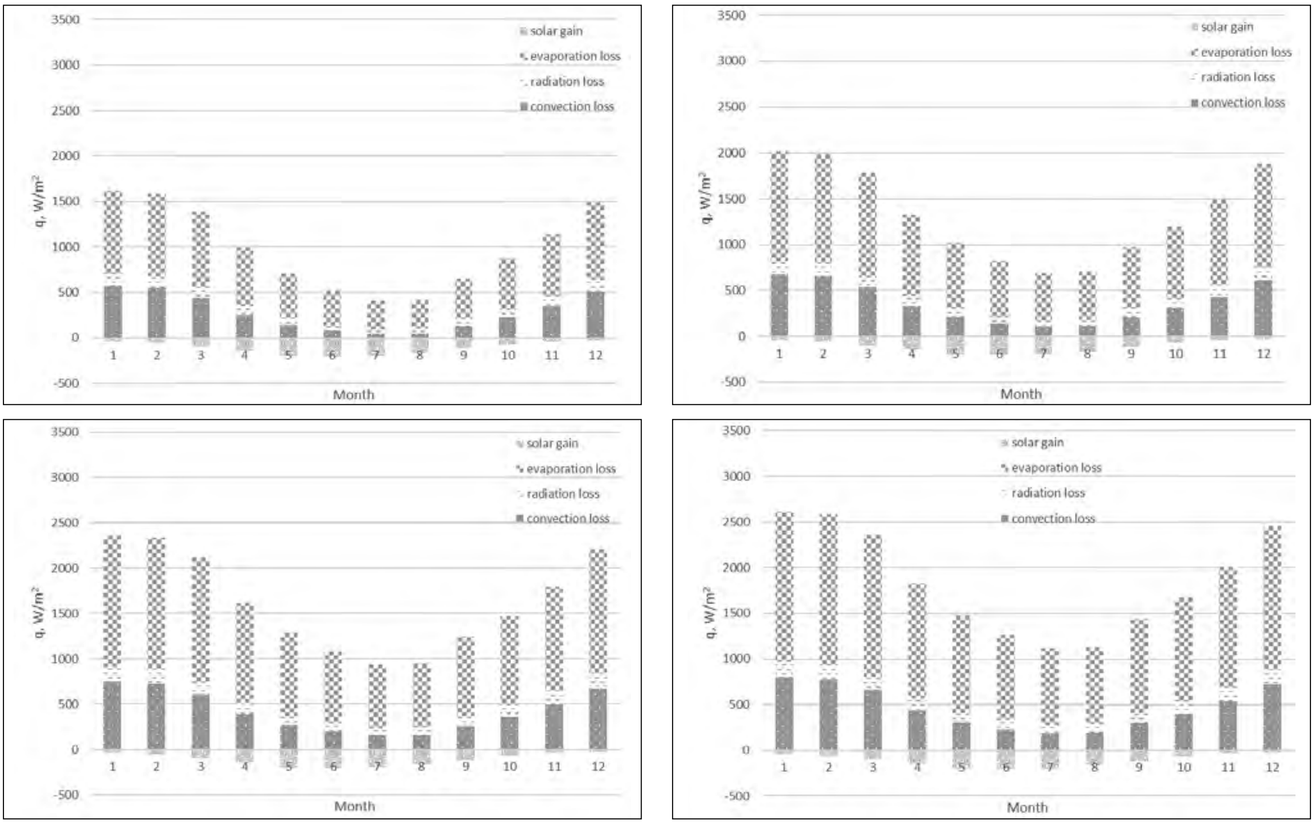
Fig. 4.
Average monthly ambient temperature for Lądek Zdrój town [12]
Rys. 4. Średnia miesięczna temperatura powietrza zewnętrznego dla miejscowości Lądek Zdrój [12]



Rys. 5.
The long-term average monthly sum of solar radiation energy per horizontal surface for Kłodzko city [14]
Rys. 5. Wieloletnia średnia miesięczna suma energii promieniowania słonecznego na powierzchnię poziomą dla miejscowości Kłodzko [14]

from the water surface for each temperature level was determined and divided into its individual components. These results are shown in Figure 6. As can be seen, the heat loss flux density is strongly related to the air temperature. For this reason, heat losses in the winter months are 2-3 times greater than in the summer months. The water temperature also significantly influences the level of losses. Increasing the water temperature from 20 to 33 °C causes a threefold increase in heat flux.

The highest share of heat loss is loss due to water evaporation. Its share is 62-70% and increases with increasing water temperature. The second largest loss is the convection loss. It affects a 23-28% share in the total losses, however, with increasing water temperature, this share decreases. The heat loss with the lowest impact is the radiation loss, the share of



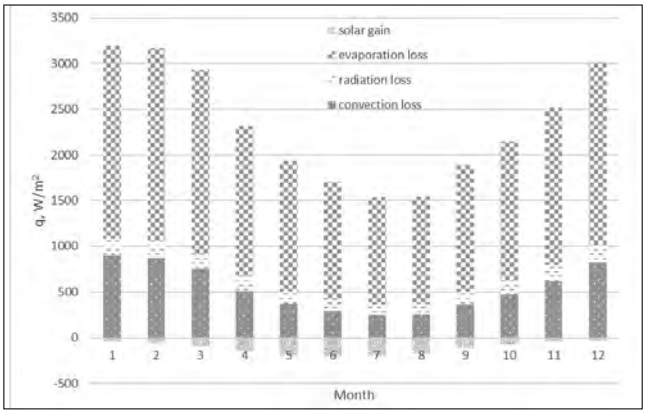


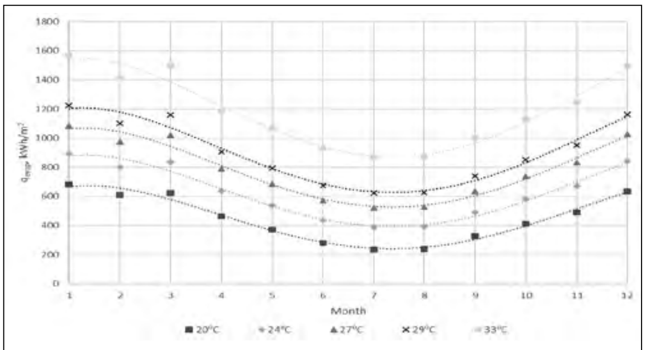
Fig. 6.
Heat loss and gains flux density for water temperature: 20 °C (top left), 24 °C (top right), 27 °C (middle left), 29 °C (middle right), 33 °C (bottom)
Rys. 6. Gęstość strumienia strat i zysków ciepła dla temperatury wody: 20 °C (lewy górny), 24 °C (prawy górny), 27 °C (lewy środkowy), 29 °C (prawy środkowy), 33 °C (dolny)

which is 7-9% and it decreases with increasing water temperature.

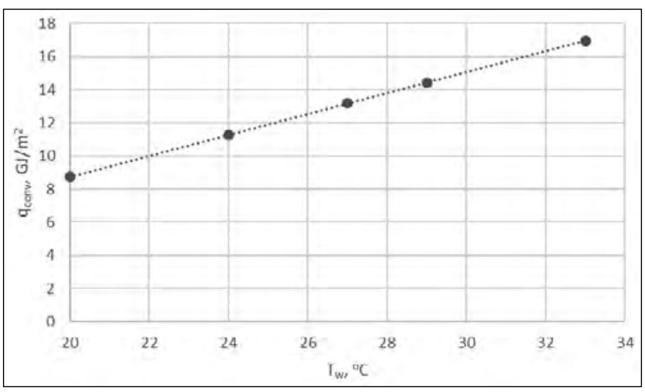
Part of the losses is covered by the use of heat gains from solar radiation. As the water temperature increases, the share of heat loss compensation by using heat gains decreases from 13% to 5%. This has an impact on an increased share of heat loss caused by water evaporation in the heat balance to 71% for a water temperature of 20 °C and 74% for a water temperature of 33 °C.

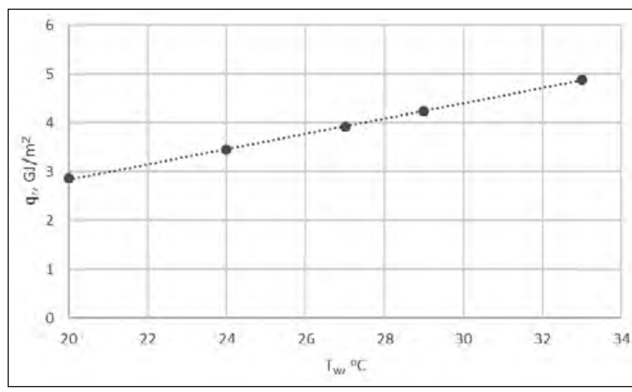
The loss of greatest importance is the loss of "wet heat", i.e. the loss of heat through water evaporation. The unit value of this heat loss increases with increasing water temperature and decreasing outdoor air temperature. The change in the value of this loss for the analysed temperature levels in individual months of the year is shown in Figure 7.

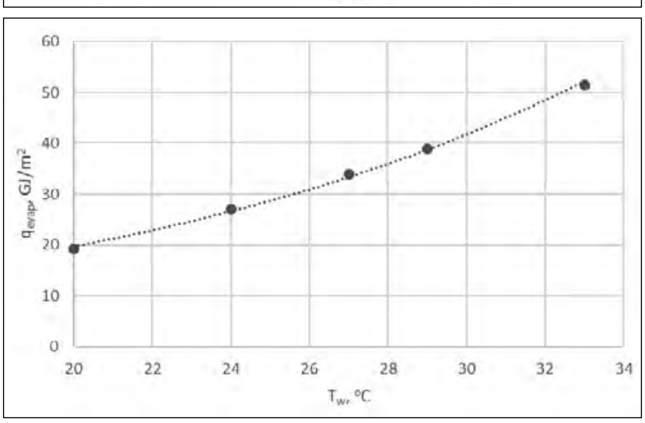
Fig. 7.
Heat loss due to evaporation
Rys. 7. Jednostkowe straty ciepła przez parowanie

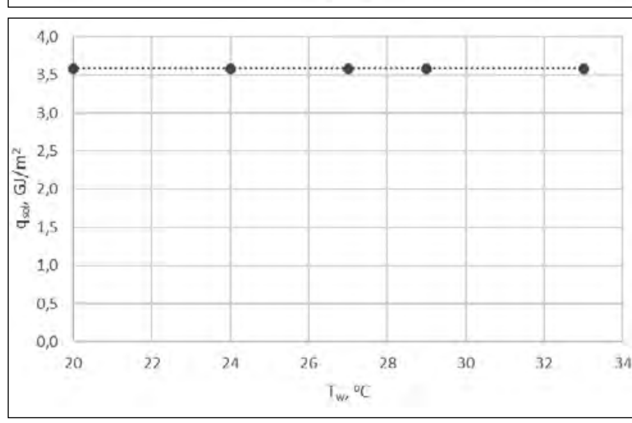


The values of annual heat losses for their individual components increase with increasing water temperature, however, the shape of these changes is not the same in every case (Figure 8). Convection loss increases linearly with increasing water temperature. The radiation loss depends on the difference of the fourth powers of the water surface temperature and the surrounding temperature, however, in the analysed range of water temperature, this loss is very well approximated by a straight line. The greatest loss i.e. evaporation loss, increases exponentially with increasing water temperature. The increase of water temperature significantly increases the heat loss. The heat gains, which were determined on the basis of the annual sum of solar radiation energy reaching the water surface, do not depend on the water temperature and in each case reduce the total heat losses by the same value. Since the









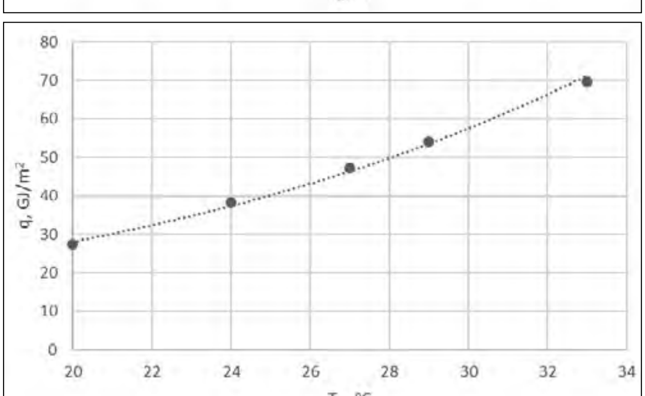


Fig. 8.
The impact of water temperature on the unit annual heat losses and gains: convection loss (upper left), radiation loss (upper right), evaporation loss (middle left), solar radiation gain (middle right), total heat losses (lower)
Rys. 8. Wpływ temperatury wody na jednostkowe roczne straty i zyski ciepła: strata konwekcyjna (lewy górny), strata radiacyjna (prawy górny), strata parowania (lewy środkowy), zyski promieniowania słonecznego (prawy środkowy), sumaryczne straty ciepła (dolny)

greatest loss is evaporation loss, which increases exponentially with water temperature, the total unit heat loss from the water surface also increases exponentially with increasing temperature.

Figure 9 shows the values of the unit heat demand needed to maintain a constant water temperature, divided on seasons. In the summer months the demand is the lowest and ranges from 2.1 to 11.2 GJ/m^2 depending on the water temperature, its share in the annual heat demand ranges from 8-16% and tends to increase with increasing water temperature. In spring and autumn, the demand for heat is on a comparable level, ranging from 6.4 to 17.9 GJ/m^2. The share of this demand in relation to the annual demand is not dependent on the temperature and totals 26% in spring and 24% in the autumn months. The greatest demand for heat occurs in winter and ranges from 11.8 to 24 GJ/m^2, its share in the annual heat demand decreases from 43% for water temperature of 20 °C to 34% for a water temperature of 33 °C.

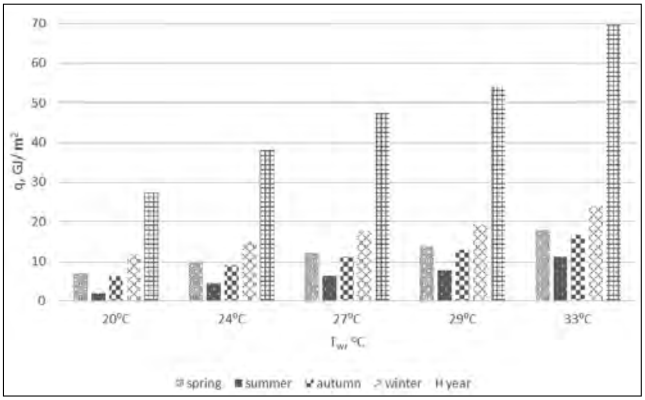


Fig. 9.
Unit heat demand as a function of water temperature, calculated for each season
Rys. 9. Jednostkowe zapotrzebowanie na ciepło w funkcji temperatury wody, dla poszczególnych pór roku

Conclusion

The aim of conducted analyses was to assess the energy consumption of the process of the year-round stabilization of water temperature in open-air swimming pools. Analyses show that the most important heat loss mechanism is heat loss with water evaporation. The share of this loss is 63-70%. In addition, this loss increases exponentially with temperature, so its share increases significantly at higher water temperatures. Convective loss is the second largest component of losses and its share for the analysed case was 23-28%, due to the fact that the analyses were carried out for a town located in the mountains, which was characterized by lower average temperatures and higher average wind velocity than in lowlands. Radiation loss he lowest value among the analysed heat loss mechanisms. Its share was 7-9%. Part of the heat loss can be covered by using the heat gains from solar radiation. Their share in the year-round heat balance is 5-13%.

The presented results show that maintaining a constant temperature in outdoor swimming pools is a process that requires high energy expenditure. This demand increases exponentially with increasing water temperature, and the loss related to water evaporation has the greatest impact on such large losses. Limiting this loss, e.g. by using pool shutters in periods when they are not in use, could significantly reduce energy expenditure. Seasonal operation of such facilities would also allow reducing energy demand – the share of the summer period in the annual energy needs is 8-16%, while the period from spring to autumn stands for 57-66% of annual energy needs.

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