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Original article

Rate of Evaporation when Water Surface is Blown by a Decelerating Air Flow

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Abstract
Purpose. The purpose of the work is to investigate the impact of the longitudinal profile of air flow velocity on the evaporation process, and to consider the accelerating, uniform and decelerating air flows.
Methods and Results. The process of evaporation from the water surface blown by wind, the speed of which varied within the range 0.68–7 m/s was studied in the laboratory experiments. The latter were conducted in a direct wind-wave channel at different wind field configurations conditioned by the choice of installation parameters. An open channel and a channel partially covered with a removable roof were used. The sloping roof and the preset air flow speed made it possible to obtain the accelerating, uniform and decelerating air flows. The volume of evaporated liquid was determined at the fixed values of air flow speed, water and air temperature, water surface temperature, and relative air humidity. The evaporation rate was defined from a flat water surface and in the presence of wind waves, the steepness of which varied within the range $0.1 < ak < 0.31$.
Conclusions. It has been established that the rate of evaporation from a flat surface at a decelerating air flow significantly exceeds those recorded at the uniform and accelerating ones. When wind waves are in a decelerating air flow, the evaporation rate increases with the growing wave steepness. The evaporation is additionally enhanced in case the capillary waves are present on the front slope of nonlinear wind waves.

Keywords: evaporation, evaporation rate, saturated vapor pressure, natural convection, boundary layer, vortices in a boundary layer, decelerating liquid flows, wind waves

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Introduction

Evaporation from the ocean surface is of fundamental importance for the moisture cycle and heat transfer in the ocean–atmosphere system. More than one third of all heat reaching the Earth is consumed during evaporation and released during condensation. The evaporation process supplies water vapour to the atmosphere. The evaporation rate is determined by a number of factors, one of which is the presence of wind waves. A large body of research has been devoted to this topic. Analysis of field data has shown that the height and steepness of surface waves play a significant role in evaporation intensity [1]. Maximum evaporation intensity is reached in shallow waters during storms [2]. In [3], an estimate of the increase in evaporation due to the presence of waves and storm intensification in the shallow northern Caspian Sea was provided. Studies [4–6] demonstrate that temperature and humidity depend on wind speed and the presence of wind waves on the water surface. In [3, 7], the seasonal character of this dependence, conditioned by water body depth and wind wave parameters, was estimated. When the wave steepness reaches a critical value, crest breaking occurs, forming "plunging" and "spilling" breakers [8]. This process leads to an increase in evaporation intensity (e.g., by 15% at a wind speed of 10 m/s in the northern Caspian Sea) [3]. In [9], an experimental study of the impact of wind speed on the evaporation rate of seawater from a layer with a flat surface was performed.

Another important factor governing wave–air flow interaction is the generation of capillary waves on the slopes of energy-bearing waves. Several mechanisms for generating such waves have been proposed. In [10], the increase in evaporation is associated with the growth of the steepness of energy-bearing waves as the wind intensifies. It is assumed that when the steepness of the primary wave reaches a critical value, the surface tension at its crest must reach a local maximum, generating a trail of capillary waves on the front slope of the primary gravity wave. Observations confirm the appearance of capillary waves on the front slope of the primary wave and their absence on the rear slope.

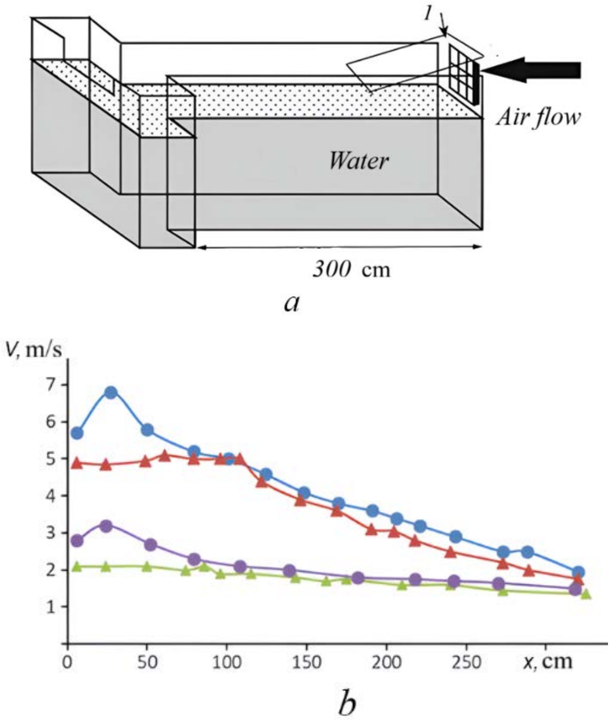
A different mechanism is proposed in [11], where it is assumed a priori that capillary waves, termed "parasitic ripples" by the author, exist across the entire surface of the energy-bearing waves. It is noted that these waves prevent the experimental acquisition of a detailed picture of the flow in the viscous layer. As an alternative, direct numerical simulation (DNS) of flow over a wavy surface in the presence of sinusoidal capillary ripples, imposed artificially, is employed. The appearance of lambda-vortex structures in the boundary layer of the air flow was discovered, with vortices detaching from the water surface and ascending into the bulk of the air flow.

Since the time of Kelvin, Jeffreys, and Shuleikin, the generation of capillary waves has been linked to the formation of vortices on the front slope of the primary wave, where the wind speed decreases in the fetch direction due to the expansion of the air flow. The paper [12] experimentally demonstrates that in a decelerating fluid flow near a flat interface, the viscous layer undergoes periodic arrest due to friction at the lower boundary of the layer and an adverse pressure gradient at the upper boundary. Inside the boundary layer, loss of stability of laminar flow occurs and chains of vortices form, the diameter of which is on the order of the viscous layer thickness [13]. In [14], it is shown that vortices in the air flow near the water surface deform the surface through a reduction in pressure beneath the vortex, thereby generating capillary waves. These vortices play an important role in enhancing evaporation, since they form near the water surface in the zone of maximum humidity and rise into the bulk of the flow under the action of the generalized Joukowski force.

The evaporation rate is also important for the desalination of seawater, which is a potential source of fresh water. The purpose of the present work is to investigate the impact of the longitudinal velocity profile of the air flow on the evaporation process, and to experimentally determine the evaporation rate from a flat water surface and from a wavy surface in a decelerating air flow and in an air flow with a uniform longitudinal velocity profile, for identical thermohydrodynamic parameter values.

Apparatus and experimental procedure

The experiments were conducted in the laboratory wind-wave channel of the Department of Sea and Inland Water Physics, Faculty of Physics, Lomonosov Moscow State University. The experimental setup is shown in Fig. 1, *a*.



F i g. 1. Installation scheme (*1* – inclined removable roof on section $x < 1$ m) (*a*); longitudinal profiles of wind speed at its different values: lines with blue and purple circles denote the channel without roof, lines with red and green triangles – the channel partially covered with roof (*b*)

The length of the straight section of the channel with a constant cross-section is 3 m; the width of this section is 0.15 m. At the outlet, the channel width increases to 0.45 m (section length 0.5 m), which reduces wave amplitude and wind speed at the channel exit. Standing waves were not observed in our experiments at the wind speeds under study. The wind generator supplied air to the channel through a grid of parallel rectangular cells, providing a plane-parallel air flow.

Similar, though larger, experimental setups are commonly used for studying wind waves. Study [15] describes wind-wave channels with dimensions of 15 × 0.8 × 1.6 m (Kyoto Institute), 15 × 0.4 × 0.4 m (Institute of Applied Physics, Russian Academy of Sciences), and 6.5 × 0.3 × 0.8 m (Kindai University); water depths during experiments were 0.8, 1.5, and 0.5 m, respectively; wind speeds in the ranges 4.7–43 and 8.5–21 m/s were measured using laser anemometers; water level fluctuations were assessed with wire wave gauges and Pitot tubes; a closed-loop air supply circuit was used, which limits the study of evaporation to the range of high relative humidity values.

To determine the cross-section-averaged air velocity field in our experiment, an RGK AM 30 anemometer was used; it was placed above the water surface on the channel axis in the region where the mean air velocity did not vary with height. This vertical coordinate was determined from self-similar profiles [16]. To achieve a maximum wind speed of 7 m/s, the uniform segment of the vertical profile was located at vertical coordinates above 5 cm relative to the undisturbed water surface level, consistent with the experimental results of other authors [17, 18]. The measurement uncertainty of the air flow velocity was ±(0.5 + 0.05*u*), where *u* (m/s) is the measured air flow velocity.

Time-averaged values of water temperature, air temperature, and relative air humidity in the laboratory were measured using an NGY 301A weather station with a remote sensor. The temperature measurement uncertainty was 0.1 °C; relative air humidity uncertainty was ±5% of the reading, but not less than 1%. Experiments were conducted for 4–5 hours during daylight hours, without artificial lighting. The mean air temperature in the laboratory was 21–24 °C, and relative air humidity was 18–19%. To determine the evaporation rate, the displacement of the water level over time was measured and recorded once per hour throughout the experiment. The level position was determined using a point gauge needle against a scale with a graduation of 10^{-4} m. To characterize wind wave parameters, video recordings of water surface displacement were made. No accumulation of dust on the water surface was observed during the experiments.

Method for determining the evaporation rate

To determine the evaporation rate from the water surface, a set of empirical formulae was employed. In accordance with Dalton's empirical law (1803), the evaporation rate E can be expressed as:

$$E = cp(1-q)\,, \tag{1}$$

where p is the saturated vapour pressure at the water surface temperature; q is the relative air humidity in the laboratory expressed as a fraction (the product qp being the partial pressure of water vapour in the air at the temperature and relative humidity prevailing in the room); the empirical coefficient c accounts for the influence of the air flow velocity on the evaporation rate.

A review and analysis of existing empirical formulae for the evaporation rate under air flow over a water surface is provided in [19, 20]. An example of the proposed relationships for calculating the evaporation rate and the empirical coefficient c for air flow over a flat water surface at air flow velocities $u < 3$ m/s can be found in [21]:

$$c = a + bu,\ a = 0.000116,\ b = 0.000126. \tag{2}$$

Here u is the cross-section-averaged air flow velocity; the coefficients a and b are given for calculations in SI units. Study [22] demonstrates that in the same air flow velocity range, wind waves do not form on the water surface, which is consistent with the condition that formula (2) is applicable to a flat water surface only.

In the present work, an experimental investigation of the effect of capillary-gravity wind waves in the generation zone on evaporation from a water surface was conducted under the condition $p(1-q) > 0$. By definition, the evaporation rate of a liquid equals the volume or mass of liquid evaporated per unit surface area per unit time:

$$E = \frac{m}{ST} = \rho \frac{V}{ST} = \rho \frac{h}{T}, \quad (3)$$

where m is the mass of liquid of density ρ evaporated from area S over time T. If the water temperature changes only slightly during the experiment and the water surface area in the channel remains constant, the evaporation rate is determined by the thickness of the water layer h evaporated over time T.

Since the change in water surface level was recorded once per hour, this level change determined the thickness of the water layer evaporated from a unit area over that time interval. The order of magnitude of h per hour was tenths of a millimetre. In the experiment, the evaporation rate was determined for a prescribed air flow velocity. Taking into account formulae (1)–(3), the parameter c was defined as the ratio of the evaporation rate to the partial pressure difference in the boundary layer of the air flow:

$$c = \frac{E}{p(1-q)} = \frac{\rho h}{Tp(1-q)}. \quad (4)$$

Thus, the evaporation rate is a linear function of the difference between the saturated vapour pressure at the water surface and the partial pressure of water vapour in the air at the temperature and relative humidity of the laboratory [23]. The empirical formulae for calculating the evaporation rate presented in [19, 20] account for such primary parameters as convection and air flow over the water surface, but do not always take into account the influence of water surface deformation or surface films of various types on the evaporation process. The proposed method for calculating the evaporation rate makes it possible to investigate this influence experimentally.

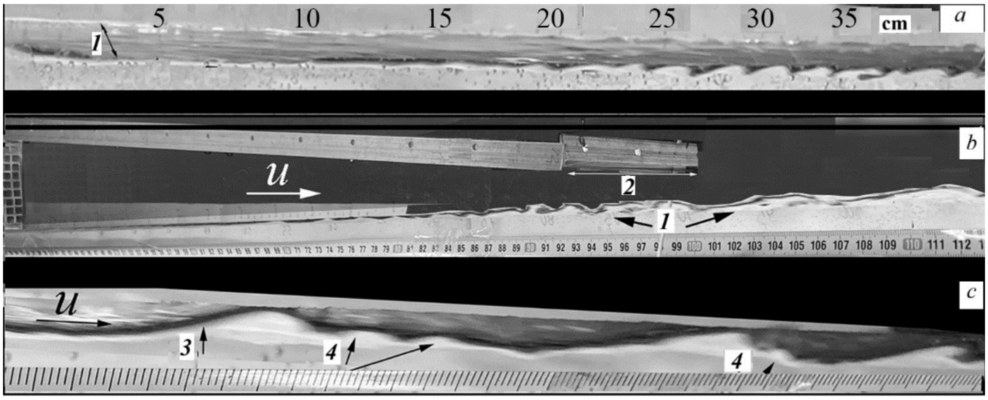
Discussion of experimental results

In the conducted experiments, the evaporation rate from the water surface was determined in an open channel and in a channel with a sloping roof at air flow velocities of 0.68–7 m/s. The removable roof was installed at an angle to the horizontal, making it possible to obtain the desired longitudinal air flow velocity profile. In the converging channel, an accelerating air flow was formed; in the diverging channel, the air flow decelerated. To produce a uniform air flow, the roof was set at a small angle to the horizontal, forming a converging channel. A uniform air flow was established when the increase in air flow velocity along the channel was fully compensated by friction losses. With the horizontal roof installation (as in the open channel), the air flow velocity decreased along the longitudinal axis due to friction at the boundaries.

In the first series of experiments, the mean air flow velocity in the uniform part of the vertical profile (5 cm above the water surface) did not exceed 3 m/s. In this series, wind waves did not form on the flat water surface, consistent with the results of [22]. In the second series, the air flow velocity at the channel inlet was set in the range 3–7 m/s. In each experiment, the longitudinal air flow velocity profile was determined in the open channel and in the channel with a roof (Fig. 1, *b*).

As can be seen from this figure, the air flow velocity beneath the sloping roof (lines with red and green triangles) does not vary along x in the section $x < 1$ m, which was achieved by selecting the appropriate roof inclination angle. The air flow velocity in the open channel decreases along its entire length, beginning at the coordinate $x = 0.15$ m. The air flow velocity under the roof is lower than in the open channel at the same horizontal coordinate value. Beyond the edge of the roof, in the section $x > 1$ m, the air flow velocity decreases along x. In the zone of air flow deceleration in both the roofed channel and the open channel, stable wind waves form when the air flow velocity exceeds 3 m/s [24].

Fig. 2 shows the water surface at the inlet to the open channel, near the edge of the roof, and in the wave amplification zone at an inlet air flow velocity of 7 m/s. In the section $0 < x < 15$ cm, stable wind waves are absent (Fig. 2, *a*). According to the data in Fig. 1, the air flow velocity increases along the horizontal coordinate in this section. In accordance with [22], waves do not form in an accelerating air flow because chains of vortices do not develop in the viscous layer of the air flow. In the zone of air flow deceleration ($x > 15$ cm), regular short waves with a length of 2 cm length are visible on the water surface in the open channel (Fig. 2, *a*), which is consistent with the results of that study.

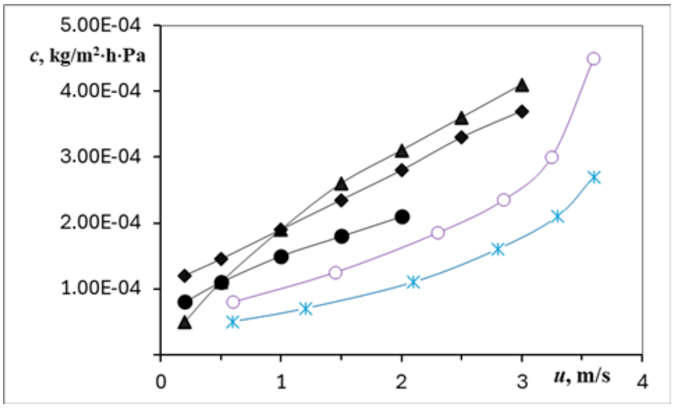


F i g. 2. Photograph of water surface during the experiment: *a* – zone of wind wave generation at the beginning of the open channel ($x > 0.15$ m); *b* – channel under the roof; *c* – nonlinear wind waves (*1* – water surface; *2* – roof end; *3* – back slope of nonlinear wave; *4* – capillary waves on the front slope of main wave)

Fig. 2, *b* shows the channel section adjacent to the edge of the sloping roof; no wind waves are present on the water surface under the roof. In this section, the air flow velocity does not vary along the x-axis (Fig. 1). According to [22], in a uniform air flow, chains of vortices do not form in the boundary layer near the water surface that could produce regular wave deformation; at coordinates $x > 1$ m, wind waves with a length of 5 cm length are visible in the zone where the air flow velocity decreases along the x-axis. Fig. 2, *c* shows nonlinear wind waves with a gentle rear slope. Capillary waves with a length of 1 cm length are visible on the front slope. These waves arise in the zone of air flow expansion when the air flow velocity exceeds the phase speed of the waves (young waves) [22, 24]. According to those references, wave generation is caused by the action of chains of cylindrical vortices that form in the viscous layer of the decelerating air flow, where the air humidity is at its maximum. Moving into the bulk of the air flow under the action of the generalized Joukowski force, the vortices transport humid air, thereby intensifying the evaporation process. Study [25] demonstrates that the period of vortex ejection and the spacing between vortices decrease as the air flow velocity and its longitudinal velocity gradient increase. In this case, the number of vortices forming per unit time increases, leading to a higher evaporation rate.

Fig. 3 presents the experimental dependences $c(u)$, covering the full investigated air flow velocity range $0.68 < u < 7$ m/s. At $u < 3$ m/s, the dependence $c(u)$ is linear with the respect to air flow velocity.

As shown in Fig. 3, the evaporation rate in the open channel is higher than in the channel partially covered by the roof. Comparison of data obtained at $u < 3$ m/s (no regular wind waves) in the converging and diverging channels shows that evaporation in the diverging channel is higher, which is attributable to the formation of vortex chains.



F i g. 3. Experimental $c(u)$ dependencies: line with transparent circles shows the open channel, with crosses – the channel with roof (solid line marks approximation); line with triangles denotes the data from [19], with diamonds – from [21], and with dark circles – from [26]

These data made it possible to compare the $c(u)$ dependence with a number of empirical formulae and experimental data from other authors for a flat water surface at $u < 3$ m/s [19–21, 26]. For all studies, nearly linear $c(u)$ dependences were obtained, as in formulae (1) and (2). The data exhibit considerable scatter [27]. The evaporation coefficient in our experiments is lower compared to data from other authors, although the scatter falls within the same bounds. The reduction is attributable to the presence of the roofed channel section with a uniform longitudinal air flow velocity profile. In this section, evaporation is driven solely by natural convection in the plane-parallel air flow. In addition, there is a section at the channel outlet where the wind speed drops rapidly due to wall friction, which also reduces the evaporation rate.

In the second series of experiments, the wind speed exceeded the critical value at which wind waves form on the water surface, $u > 3$ m/s [22]. As can be seen from the data in Fig. 3, evaporation rises sharply, since the number of vortices forming per unit time in the viscous layer of the air flow increases. As a result, instead of the linear dependence $c(u)$ obtained at wind speeds $u < 3$ m/s, a strongly nonlinear dependence $c(u)$ appears at $u > 3$ m/s.

It should be noted that an additional contribution to the increase in the evaporation rate due to moisture transport by vortex chains is provided by the diameter of the cylindrical vortices, which amounts to several millimetres. The evaporation rate from droplets of small size and greater surface curvature is far higher than the rate from a flat water surface, since diffusion carries away all molecules leaving the droplets [28].

Conclusion

The paper proposes a methodology for studying the evaporation process from a water layer surface under the action of a plane-parallel air flow in a straight wind-wave channel. The use of a sloping roof over part of the channel made it possible to produce, in the experiments, air flows with a velocity that was uniform along the longitudinal axis of the channel, as well as flows with a velocity that decreased in the direction of motion. On the basis of the foregoing, the following conclusions can be drawn.

1. An experimental investigation of the effect of the longitudinal wind velocity profile above a water layer on the evaporation rate has been carried out.
2. It has been found that in flows with a uniform longitudinal velocity profile, the evaporation intensity is substantially lower than in a decelerating flow, since evaporation is driven solely by natural convection in the plane-parallel air flow.
3. It has been shown that in a decelerating air flow, evaporation intensity increases due to the formation of a chain of cylindrical vortices in the boundary layer. The vortices form near the water surface, where air humidity is at its maximum, and rise into the bulk of the air flow under the action of the generalized Joukowski force. The evaporation coefficient increases by a factor of one and a half to two.
4. An additional increase in the evaporation rate occurs upon the generation of wind waves at $u > 3$ m/s. The air flow envelops the wave, with velocity increasing over the rear slope and decreasing over the forward slope. In the zone of air flow deceleration (the zone of maximum humidity) above the forward slope of the wave, chains of vortices form and, under the action of the generalized Joukowski force, rise into the bulk of the air flow, increasing evaporation intensity. The vortex diameter is of the same order as the viscous layer thickness, several millimetres. The evaporation rate from the surfaces of such vortices is higher than from the flat surface of the water layer.

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Irina N. Ivanova – visualization, processing and interpretation of results, text editing, literary analysis

Olga N. Melnikova – conceptualization, problem formulation, research management, literary analysis, writing of original text

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.