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Wind tunnel measurements and numerical simulations of water evaporation in forced convection airflow

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ABSTRACT

The aim of this work is to investigate the relationship between evaporation from heated water surfaces and mean aero thermal properties of a forced airflow. Flows with Reynolds numbers varying between 2475 and 49,503 were considered. Both wind tunnel measurements and numerical simulations were used. The experimental results were obtained in an installation consisting of a low speed wind tunnel and an evaporation tank. The numerical study was performed through a 3D-CFD code. To validate the numerical formulation the predicted results were compared with the experimental measurements for the mass transfer at the free surface of the water tank and with correlations available in the literature. A good agreement was achieved which indicates an interesting capacity of the CFD program to predict the phenomena engaged.

The dependence of the rate of evaporation with air velocity, water–air temperature difference and relative humidity is also addressed. The results obtained with both methodologies clearly show that the rate of evaporation is mainly dependent of the airflow velocity. The water–air temperature difference and the relative humidity also have an important effect, but much less than the airflow velocity. For small airflow velocities the rate of water evaporation is also small and presents only a slightly dependence from the temperature difference and the relative humidity.

1. Introduction

There is a wide range of situations where the exchange of mass and heat across an air–water interface takes place. The heat and mass transfer between a water surface and the neighborhood environment is present in a wide range of outdoor and indoor situations. The heat and mass transfer between a water surface and the neighborhood environment has a significant impact on the earth climate and is present in different industrial processes and in various human activities [1–3]. When water evaporation takes place indoors, it can lead to inappropriate humidity values. Then, thermal comfort is compromised or energy is consumed by HVAC equipment to maintain adequate indoor air conditions [4].

The evaporation process is led by the heat and the mass transfer mechanisms at the water–air interface [5–7], but it is also significantly influenced by surrounding conditions [8]. Heat and mass transport occur simultaneously and are mainly driven by the mechanisms of advection, diffusion and turbulent transport [3,8]. Under natural convection conditions, the temperature gradient constitutes the driving potential for heat transfer and the existence of a concentration gradient for some species in a mixture provides the driving potential for the transport of that species [2,6,7,9]. However, even with feeble airflow velocities the influence of other parameters arises, namely the airflow velocity itself and the turbulent mechanisms [8]. Also, it is well established that in the evaporation process the latent heat of vaporization is mainly achieved by cooling the surface of the liquid [5].

A wide range of correlations is available in the literature for predicting water evaporation rates on free water surfaces. In order to determine which of these correlations can be considered reliable, Pauken [10] carried out an exhaustive experimental study using a heated pool into a low speed wind tunnel. The studied evaporation

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regimes combined turbulent free and turbulent forced convection and particular attention was given to the characterization of the limits where either free or forced convection effects may dominate. From the comparison of the results obtained with several equations based on other experiments in laboratory wind tunnels, Pauken [10] concluded that not all of the predictive equations proved to be accurate. He identified as the most truthful equations based on wind tunnel measurements those of Carrier [11] and Rowher [12]. However, research about evaporation phenomena is usually focused on the rate of water evaporated and does not address all the phenomena involved. Thus, methodologies with the ability to provide a more detailed analysis should be used.

There are various published studies on the characterization of flow and transport of water vapor from the air side, particularly in the layers immediately above the free surface. Among these, stand out the numerical studies performed by some authors [6,7,9,13], where the rate of water evaporation and the velocity field of air and water in natural convection situations were analyzed. Using two dimensional numerical models they have simulated the flow of water and air in confined or in unconfined situations for several different thermal conditions (including stable, unstable and neutral thermal stratification). All of them conclude that, in free convection, the evaporated mass flux mainly depends on the temperature of the liquid–gas interface and on its difference with respect to air temperature. However, the published studies concerning water evaporation under forced convection stand out that in this situation the effects of thermal driving forces are weak in comparison to the mechanisms of advection, diffusion and turbulent transport [1–3,8].

Using particle image velocimetry (PIV), Bukhari and Siddiqui [13,14] performed an experimental study of the velocity fields in the zone below the air-liquid interface and detected turbulent structures. Based on the results obtained they concluded that the flow of the water side is three-dimensional and presents complex structures.

Turbulence is a complicated form of fluid motion with a great possibility of occurrences. Its simulation requires the use of a numerical model. The most widespread turbulence models employ the eddy-viscosity concept and are known as k–ε models. These models employ two transport equations, one for the turbulent kinetic energy (k) and another one for the turbulent kinetic energy dissipation rate (ε), from which the k and ε fields are calculated [4,15].

The two-layer k–ε turbulent model for high-Reynolds-numbers of Chieng and Launder [16] incorporates a simplified, yet consistent, formulation. In fact, this model is an improvement of the *standard* high-Reynolds k–ε model [17,18], which is the most widely used and validated classical turbulent model [4]. Maintaining the stability of the high-Reynolds k–ε model, the Chieng and Launder model can be used with coarse and refined near-wall grids [19,20]. In the Chieng and Launder model the flow boundary layer is assumed to be split into two sub-layers, with the nearest to the wall driven by the viscosity of the fluid and the other dominated by inertial forces. The flow properties in each sub-layer are specified by semi-empirical expressions known as wall-functions. The position of the interface between these sub-layers is established in a way that ensures the continuity of the wall-functions values when passing from one sub-layer to the other one and vice-versa. The Chieng and Launder model has been widely used in the numerical simulation of a wide range of complex flows involving, besides the flow, the fields of temperature, turbulence, humidity, contaminant concentration and air quality [19,21–25]. Yielding reasonable results in many applications, it became most attractive for engineers in this field, since it is easy to program and generally ensures a robust and convergent behavior of the calculation procedure.

The aim of this work is the study of the phenomena of evaporation at free heated water surfaces and the analysis of the influence on this process of parameters such as the airflow velocity, the air relative humidity and the difference of temperatures between water and air.

A truthful analysis of the indoor environment demands a very detailed representation of the fields of velocity, temperature and air moisture and the transport of water vapor by the air movement within the enclosure. An appropriate approach able to answer these requests is the computational fluid dynamics (CFD) methodology. An existing 3D-CFD program based on the control volume finite difference methodology was extended to incorporate the numerical simulation of flows with evaporation and condensation. This code has already been tested and successfully used to solve natural, mixed and forced sensible heat convection problems, e.g. Raimundo et al. [21–23]. Then, another objective of this work is to check the capacity of this program to predict also water evaporation and condensation and water vapor transport through the calculation domain.

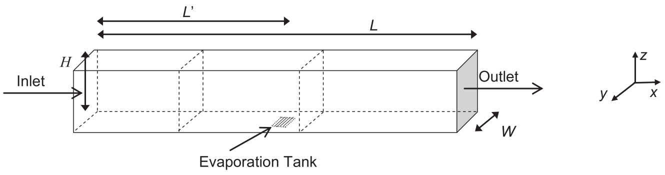
It is common in the CFD analysis to simply take into account a constant value of the vapor pressure for the whole airflow domain. However, with this feature the moisture distribution in the indoor air and its impact on the internal flow and on the evaporation from water surfaces is only roughly evaluated [4]. To overcome these limitations, the CFD methodology used here considers the dry air and the water vapor as independent non-reacting fluids.

Due to its accuracy, stability, simplicity of application and demanded computational resources, the two-layer k–ε turbulent model for high-Reynolds-numbers of Chieng and Launder [16] was adopted. This model answers fairly well to all the demands listed before. However, some adaptations were introduced in order to produce accurate results of the rate of evaporation at air–water interface.

The extended numerical model was thoroughly tested by comparing the predicted results with those from experiments and with those from the literature. The validation process, only partially presented in this paper, was done comparing airflow velocities and mass transfer fluxes at the free surface of a water tank. Therefore, the experimental setup is first briefly presented, followed by the airflow, the transport of chemical species and the turbulence model.

2. Experimental apparatus and procedures

The experimental installation where the tests were performed consists of a low velocity wind tunnel, working in aspiration and a container of water equipped with a heating system located inside the test chamber of the tunnel. During the experiments the water evaporation rate, the tank water temperature, the air temperature in some specific points and the air velocity field of the symmetry plane of the wind tunnel were measured [26]. The test chamber of the wind tunnel (Fig. 1) has a square cross-section of 0.40 × 0.40 m^2



L (m)	L' (m)	H (m)	W (m)
3.30	1.80	0.40	0.40

Fig. 1. Schematic representation of the experimental setup.