# Evaporation of water film from horizontal isothermal cone cavity

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**Abstract**

Experiments on natural convective mass transfer adjacent to horizontal isothermal cone cavity were performed, the water film temperature was ranging from 35°C to 75°C. Water was evaporating to moist air. Analytical equation describing the depletion of mass in cone cavity was derived and used for evaluation of mass flux and averaged mass transfer coefficients from experimental data. Sherwood numbers were determined and correlated as a function of Rayleigh number. Obtained correlation was compared with existing correlation with satisfactory discrepancy and extended the previous range of validity to $Ra_m = (0.1 \div 10^4)$.

*Key-words:* Free convection, mass transfer, evaporation, experiment

## 1. Introduction

Water surface evaporation is involved in number of technical processes: drying, evaporative cooling, food processing, nuclear spent-fuel disassembly basin loses etc. [1, 2, 3]. It is necessary to accurately estimate the mass flux to control and optimize these processes, since the heat of vaporization is major part of heat transfer from the liquid. The focus of investigations in the literature is ranging from one small droplet [1] to large pool surfaces [2]. Presented experimental study is focused on evaporation (mass transfer) from water residuum that rests in isothermally heated cone cavity as a result of imperfect drying.

The objective of the presented study is to obtain values of mass transfer coefficient correlated to a wide range of Rayleigh number, results will be further used in comparative study together with CFD.

Natural convection mass transfer was investigated by Goldstein et al. [4] using the technique of naphthalene sublimation on various horizontal geometries, $Sc = 2.5$. Lloyd and Moran [5] used the electrochemical technique for natural convection mass transfer investigations from horizontal surfaces (including disks), reaching $Sc = 2200$. To the author's best knowledge, no natural convection mass transfer experimental investigation was carried out for small circular surfaces ($d < 35mm$) for $Sc \approx (0.5 \div 0.65)$. Extensive critical review on horizontal convection was carried out by Corcione [6], but the study is focused mainly on heat transfer correlations.

## 2. Experimental apparatus

The experimental set-up is composed from a closed plexiglass box with dimensions 1m x 0.3m x 0.3m - see fig. 1. In the bottom centre of the box, a platform is placed with conic hole at the top made from duraluminium with outside wall thickness of 1.5mm. The maximum diameter of the cavity is 35mm. Inner side of the platform is part of a water circuit, that remains the walls of the platform at steady temperature with uniform temperature spatial stratification. The water is heated by electric flow-heater controlled by PID regulator using solid state relay. Temperature of the water in the circuit is measured by 3xPT100 temperature probes. The temperature of the cone cavity was ranging from 35°C to 75°C during the measurements.

Water vapour mass flux is measured optically. The water film is periodically captured by thermal camera Flir SC640. Due to the conic shape of the cavity, the residual mass in the cavity is calculated from the diameter of circular water film during the post-processing, see next chapter and chapter Calibration.

Before each measurement, the surface of the cavity is conditioned by detergent to ensure that spherical cap is not created, flat surface is required. The water film is created using distilled water.

Temperature of the air and water is measured by Pt100 using NI chassis cDaq-9188 and NI module 9216. Humidity is measured by 2 x Michell HS3 probes connected directly to the PC workstation through USB virtual serial port and Modbus protocol. As a software, LabVIEW was used.

### 2.1. Data processing

Post-processing together with measurement apparatus calibration crucially influence the resulted quality od data. A Matlab routine for automatic evaluation of radius/diameter from thermogram was created. The routine is based on Circular Hough Transform together with Phase-Coding algorithm, which are part of Matlab Image processing toolbox [7].

Based on the conic shape, it is possible to find analytical relationship for depletion of mass by time, which can serve for evaluation of mass flux of water vapour $n_{wv}$ from experimental data. Initial equation is

$$\frac{dm_w}{dt} = A \cdot n_{wv}, \tag{1}$$

where $A$ is the area of circular surface, $A = \dfrac{\pi \cdot d^2}{4}$.

$$m_w = \frac{\rho_w \pi d^2 v}{12}. \tag{2}$$

After substituting the relationship between the height of the water and surface diameter $v = d/\left(2tg(\alpha/2)\right)$, the equation for diameter as function of mass can be derived

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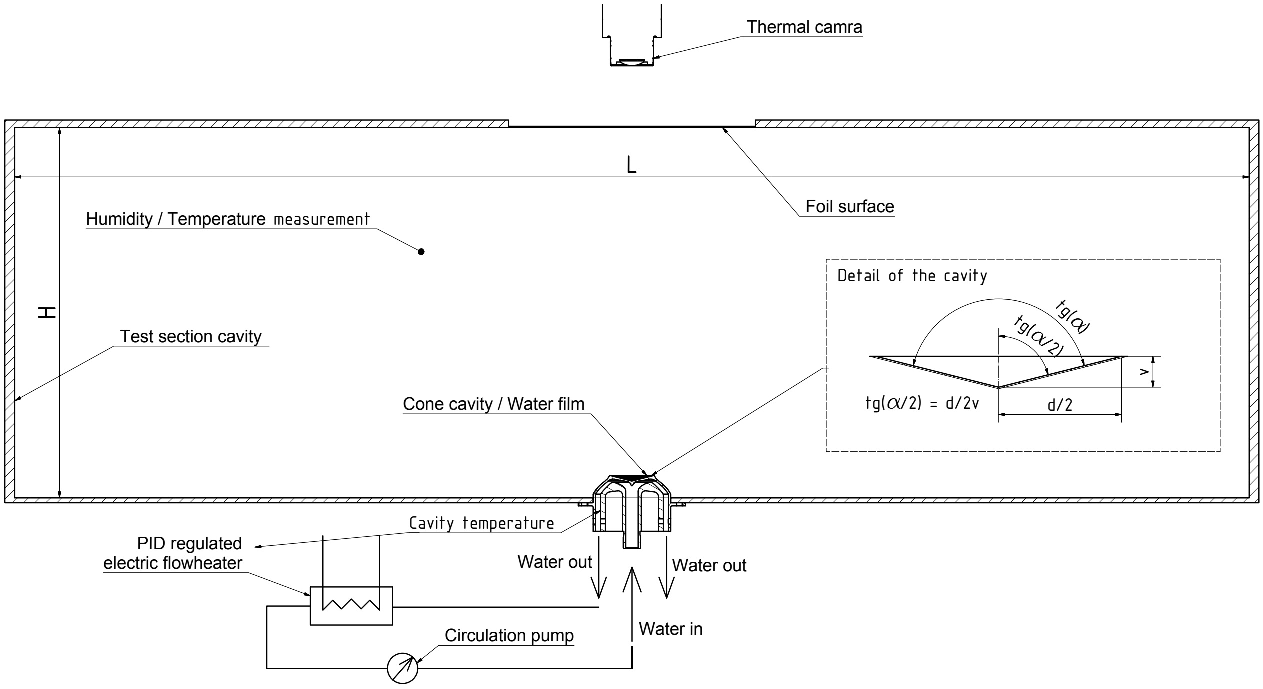


***Fig. 1.*** *Schematic diagram of the experimental apparatus: L = 1m, H = 0.3m, B = 0.3m (width); water film is observed by thermal cam, the cavity is maintained ate steady temperature by outer water circuit. In the dashed box is geometrical description of the cavity*

$$d = \sqrt[3]{\frac{24 m_w tg(\alpha/2)}{\pi \rho_w}}. \tag{3}$$

After substituting eq. (3) to to eq. (1), eq. (1) can be integrated between $t_0$ and $t$, obtaining

$$m_w(t) = \left[ m_0^{1/3} - \frac{\pi}{12} \left( \frac{24 tg(\alpha/2)}{\pi \cdot \rho_w} \right)^{2/3} \cdot n_{wv} \cdot t \right]^3 \tag{4}$$

Eq. (4) is used for evaluation of mass flux from the experimental data by regression analysis, fitted function was polynomial dependency. From the mass flux $n_{vw}$ can be evaluated the mass transfer coefficient $h_m$

$$h_m = \frac{n_{vw}}{\rho_{vw-film} - \rho_{vw-\infty}}, \tag{5}$$

where $\rho_{vw-film}$ is partial density of water vapour at the water film/air interface and and $\rho_{vw-\infty}$ is partial density of the water vapour dispersed in the moist air in the cavity, $h_m$ is averaged (or overall) mass transfer coefficient.

## 2.2. Data reduction

Two properties were varied when investigating the magnitude of water vapour mass flux: diameter of the film $d$ and on the film temperature $T$. A dimensionless representation of these two variables is Grashof mass transfer number $Gr_m$, given by

$$Gr_m = \frac{\bar{\rho}_{ma} \left( \rho_{ma-film} - \rho_{ma-\infty} \right) g L_{char}^3}{\bar{\mu}_{ma}^2}, \tag{6}$$

where $\bar{\rho}_{ma}$ is mean density of moist air $\bar{\rho}_{ma} = \left( \rho_{ma-film} - \rho_{ma-\infty} \right)/2$, $\bar{\mu}_{ma}$ is mean dynamic viscosity of moist air evaluated at $\bar{T} = \left( T_{film} + T_\infty \right)/2$. Diameter of the film $d$ is taken as characteristic length $L_{char}$.

To characterize the fluid and its ratio of momentum and mass diffusivity, Schmidt number $Sc$ is employed

$$Sc = \bar{\nu}_{ma} / \bar{D}_{wv,da}, \tag{7}$$

where $\bar{\nu}_{ma}$ is mean kinematic viscosity of moist air and $\bar{D}_{wv,da}$ is binary diffusion coefficient of water vapour to dry air.

Correlations for natural convection heat and mass transfer (for Nusselt $Nu$ or Sherwood number $Sh$) usually includes Rayleigh number $Ra$ instead of separate dependency on Grashof and Prandtl or Schmidt number

$$Ra_m = Gr_m \cdot Sc. \tag{8}$$

A dimensionless representation of mass transfer coefficient (eq. (5)) is Sherwood number $Sh$

$$Sh = \frac{h_m \cdot L_{char}}{\bar{D}_{wv,da}}. \tag{9}$$

## 2.3. Calibration

The measurement apparatus was calibrated using weigh scales Kern EW 620-3NM. A small syringe was filled by water, weighted, then water from the syringe was inserted to the conic cavity. The empty syringe was weighted again to get the precise mass of water in the cavity. The water film in the cavity was then captured by thermal camera, calibration curve is shown in fig. 2, this function is used for calculation of mass from thermograms.

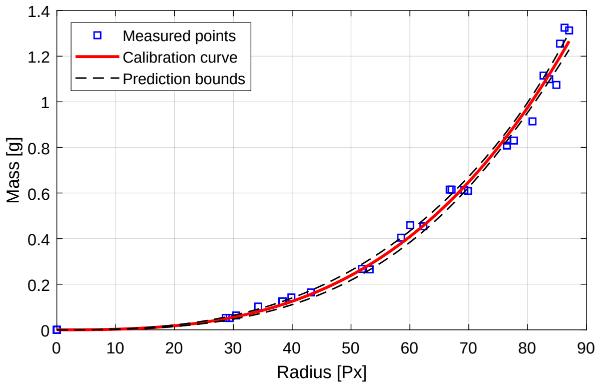


***Fig. 2.*** *Calibration curve for mass evaluation from thermograms*

## 3. Results and discussion

The magnitudes of the mass flux of the present investigation are plotted in fig. 3 as a function of temperature of the isothermal cavity and diameter of the fluid film. The temperature was varying in range 35°C to 75°C, the diameter of the fluid film was changing in range of (30mm ÷ 0mm). For the maximum diameter (30mm), the flux of water vapour for all the plotted temperatures is ranging $n_{wv} = (2 \div 17) \cdot 10^{-4} kg \cdot m^{-2} s^{-1})$ with clear dependency on temperature. For temperatures 35°C and 40°C, the flux remains almost constant in range 30mm to 15mm, then follows a slight increase.

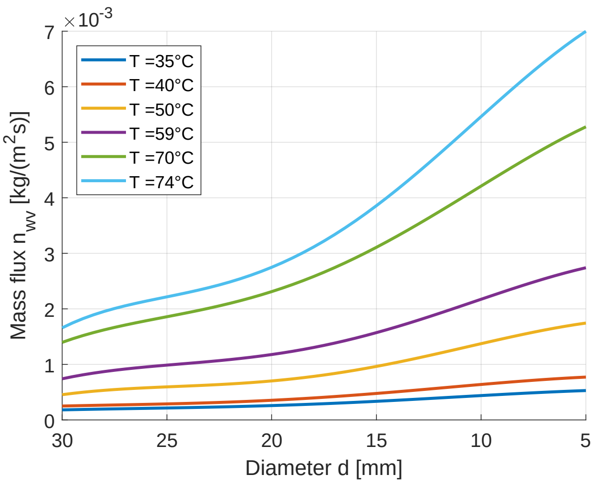


***Fig. 3.*** *Mass transfer results: dependency of mass flux $n_{wv}$ on film diameter and film temperature*

For higher temperature (50°C - 74°C), the dependency of the water vapour mass flux on diameter is bigger. The final curve of is steeper with increasing temperature. The average mass flux $n_{wv}(35°C, d = 5mm)$ is 2.9x larger than $n_{wv}(35°C, d = 30mm)$, $n_{wv}(50°C, d = 5mm)$ is 3.8x larger than $n_{wv}(50°C, d = 30mm)$ and $n_{wv}(74°C, d = 5mm)$ is 4.2x larger than $n_{wv}(74°C, d = 30mm)$. The increase can be explained by exterior effects at the boundaries of water film during the convection, since for large diameters, these exterior effects has less significant impact than for small diameters (<10mm), where these exterior effects prevails and increase the overall mass flux and mass transfer coefficient.

### 3.1. Dimensionless analysis

In fig 4 is plotted dependency of Sherwood number as a function of Rayleigh mass transfer number in logarithmic coordinates together with the two fitted functions (least square method). It is typical to enforce slope 1/4 [3, 4, 6] for correlations in laminar convection (red line), the transition region is in range $Ra_m \approx 10^7 \div 10^9$ [6, 8], for higher Rayleigh numbers, typical slope is 1/3 [6]. The data were also fitted without enforcing the slope of 1/4 (blue line). Obtained correlations in form $Sh = a \cdot Ra_m^b$ are

$$Sh = 0.987 \cdot Ra_m^{0.25}, \tag{10}$$

$$Sh = 0.939 \cdot Ra_m^{0.273}. \tag{11}$$

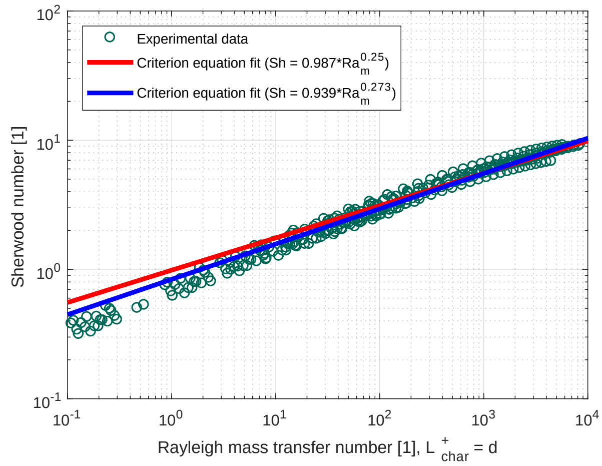


***Fig. 4.*** *Mass transfer results: Sherwood number correlation, Rayleigh number based on $L_{char} = d$. Experimental data are fitted by two criterion equations*

For $Ra_m > 10$, both curves correspond well with experimental data, for lower values, function described by eq. (11) is closer to the experimental data, since there were two variables to be fitted.

In the previous experimental works, it was common to use different characteristic length. Above presented experimental data are evaluated for $L_{char} = 4A/P = d$, where $P$ is perimeter of the water film, $A$ is area of the water film. In reference [4, 5], $L^+_{char} = A/P = d/4$ is used. The Rayleigh and Sherwood number was reevaluated with $L^+_{char}$ as characteristic length to obtain comparable results as in [4, 5]. Results for updated $L^+_{char} = d/4$ are plotted in fig. 5.

For $L^+_{char} = d/4$ it is necessary to evaluate new correlations for Sherwood number $Sh^+$ (also based on $L^+_{char}$)

$$Sh^+ = 0.692 \cdot Ra_{m+}^{0.25}, \tag{12}$$

$$Sh^+ = 0.707 \cdot Ra_{m+}^{0.244}. \tag{13}$$

Above presented correlations (eq. (12) and (13)) are very close to each other and also they follow the experimental data for the full range of $Ra_{m+}$, but due to dividing the characteristic length by $4^3$, the maximum Rayleigh number is $Ra_{m+} \approx 3 \cdot 10^2$.

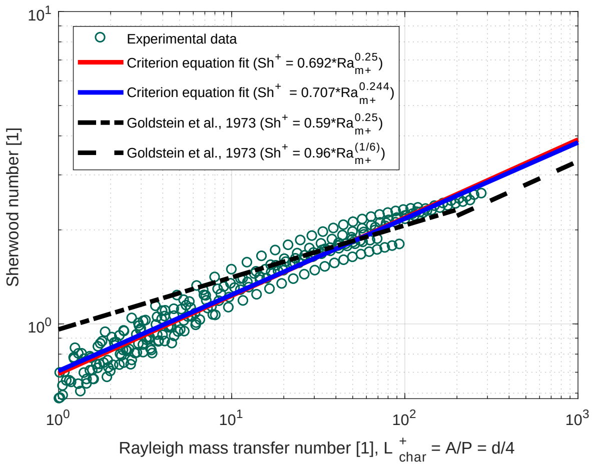


***Fig. 5.*** *Mass transfer results: Sherwood number correlation, Rayleigh number based on $L_{char} = d/4$. Experimental data are fitted by two criterion equations and compared with correlations from reference [4]*

The results can be compared with findings in reference [4]. The match is good in range $Ra_{m+} \approx 10 \div 150$, even though correlation [4] has the slope of 1/6. Correlation [4] with the slope (1/4) differs from the presented correlation based on film evaporation by 15%, but the compared criterion equation [4] is for higher Rayleigh numbers.

In fig. 4 and 5, it can be noticed, that for higher Rayleigh numbers, the dependency of $Sh = f(Ra_m)$ starts to have a smaller slope and start to decline from the fitted functions. This trend can be explained by arrangement of the experiment. Main tracked temperature in the experiment was the temperature of the isothermal cavity and this temperature is used for evaluation of dimensionless numbers. However, due to the evaporation, the water is cooled by latent heat of vaporization (and convection), which could results in lower temperature of the water surface. This effect will be further investigated and take into account during evaluation of dimensionless numbers. The increase of temperature of the water surface during the experiment could also explained the steep dependency of mass flux on diameter.

## 4. Conclusion and future steps

The evaporation rate and mass flux of water film in moist air has been experimentally investigated. Parameters influencing the mass flux have been examined, and results show that two significant parameters are temperature and diameter of the film. Experimental data were studied also in dimensionless variant. Correlations of Sherwood number were obtained. Dimensionless form allows comparing experimental data with mass transfer experiments found in literature, based on naphthalene sublimation. Good agreement with the experimental data in the literatures was observed (maximum discrepancy was ±15%).

The present experimental method will be used also for mixed convection regime. Mixed convection evaporation from water surface was investigated by Pauken [3], but for water pan with diameter $d \approx 1.18m$, where the exterior effects at the boundaries are minimized due to large evaporation area. CFD calculations of water evaporation from the isothermal cavity are carried out and are subjects of future studies.

## Acknowledgement

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS18/124/OHK2/2T/12.

## Nomenclature

| | |
|---|---|
| $A$ | area $(\mathrm{m}^2)$ |
| $d$ | diameter of the water film $(\mathrm{m})$ |
| $D$ | diffusion coefficient $(\mathrm{m}^2 \cdot \mathrm{s}^{-1})$ |
| $g$ | gravitational acceleration $(\mathrm{m} \cdot \mathrm{s}^{-2})$ |
| $h_m$ | mass transfer coefficient $(\mathrm{m} \cdot \mathrm{s}^{-1})$ |
| $L_{char}$ | characteristic length $L_{char} = d$ $(\mathrm{kg})$ |
| $L^+_{char}$ | characteristic length $L^+_{char} = d/4$ $(\mathrm{kg})$ |
| $m$ | mass $(\mathrm{kg})$ |
| $n$ | mass flux $(\mathrm{kg} \cdot \mathrm{s}^{-1} \cdot \mathrm{m}^{-2})$ |
| $P$ | perimeter $(\mathrm{m})$ |
| $t$ | time $(\mathrm{s})$ |
| $v$ | height of the water film $(\mathrm{m})$ |
| $Gr_m$ | Grashof mass transfer number $(1)$ |
| $Ra_m$ | Rayleigh mass transfer number $(1)$ |
| $Sc$ | Schmidt number $(1)$ |
| $Sh$ | Sherwood number $(1)$ |
| $\alpha$ | cavity's angle $(^\circ)$ |
| $\mu$ | dynamic viscosity $(\mathrm{Pa} \cdot \mathrm{s})$ |
| $\nu$ | kinematic viscosity $(\mathrm{m} \cdot \mathrm{s}^{-2})$ |

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