Full-scale experimental study of moisture condensation on the glazing surface: condensation rate characterization

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Abstract. Excessive indoor moisture promotes the growth of mold and condensation on building envelope, which lead to severe IAQ problems. Given the transient, unsteady heat and mass transfer problem, studies dealing with the condensation phenomenon are generally lacking in the literature, especially studies on the condensation rate prediction. Consequently, this paper presents a method to quantify experimentally the condensation rate of droplets formed on a cold glazing surface in a full-scale entirely controlled test room (6.2 x 3.1 x 2.5 m). The condensation qualitative characterization, i.e. the moment of its appearance and its growth mechanism, is achievable using a macro-photography technique. From the time-series of droplet images captured, an image post-processing method is used to detect the droplet contours and to estimate the condensation mass flow rate. Comparisons between experimental and theoretical results show some agreement, which could validate the feasibility of imaging techniques in full-scale condensation studies. Those first results are encouraging and valuable since there were no similar studies in the literature at such the scale. Further investigations are needed in order to clarify all these aspects related to the accuracy of the condensation rate quantification methodology developed in this work.

1. Introduction

Excessive indoor moisture promotes the growth of mold and condensation, which is believed to have a significant impact on the occupant thermal comfort, the indoor air quality and the building envelope durability. As a result, numerous research programs dealing with possible manifestations of moisture inside the buildings have been undertaken [1, 2]. Recently, ASHRAE has added a new chapter titled “Moisture Management in Buildings” to the well-known “ASHRAE Handbook--Fundamentals” [3]. Despite this growing interest concerning the study of heat-air-moisture transfer phenomena at the whole-building scale, there is no special focus toward the surface condensation problems. Research dealing with superficial condensation in buildings is still limited given the transient, unsteady and even instantaneous characteristic of the phenomenon. A qualitative prediction of the surface condensation is possible. One can predict the location where the condensation takes place, the time of its production and its evolution in space/time [4, 5]. However, the quantification techniques, which intend to predict the condensation rate, are lacking in the literature. Some studies were found at the micro-scale and at the room reduced-scale [6, 7]. The mass of the condensed fluid was achievable using a micrometric weight balance. No such studies were found at the room full-scale.

Consequently, the main objective of this study is to develop an experimental method to quantify the surface condensation formed on a cold glazing within a full-scale ventilated test room under realistic conditions. The measurement technique is based on a high-definition image recording coupled with a computerized image processing method. This method allows improving the current knowledge on the superficial condensation process and can have multiple technical and industrial applications: buildings (thermal comfort, indoor air quality), vehicles (condensation prediction on windshields).
2. Experimental set-up

2.1. MINIBAT test room

The experimental investigation was conducted in a full-scale test room called MINIBAT, whose environment is entirely controllable. MINIBAT is located at the CETHIL laboratory – INSA de Lyon, France. It consists of three distinct volumes: a test room where experiments are carried out, a thermal buffer zone that allows maintaining stable and reproducible boundary conditions and a climatic chamber that simulates the outdoor temperature (Figure 1a). The South facade, which is in contact with the climatic chamber, is a 1.2 cm thick laminated glazing (W × H = 2.90 m × 2.30 m).

The air is introduced into the test room via a ceiling air diffuser. The air is extracted through two air exhausts located on the North wall. This disposition increases the homogeneity of the air distribution within the test room. The supply air temperature, humidity and the airflow rate are controlled by means of a closed-loop air-handling unit. We have designed and programmed a mobile robot (Figure 1a), equipped with sensors, in order to measure the indoor air velocity, temperature and humidity fields. A detailed description of the test room and the mobile robot can be found in [8, 9].

2.2. Image recording systems

A digital camera is installed inside the test room, at the South-East lower corner, to capture pictures of condensate droplets on the glazing (Figure 1b). It is a Nikon D810 digital single-lens reflex (DSLR). Its image sensor has a size of 35.9 × 24.0 mm and a resolution of 7360 × 4912 pixels. The camera is equipped with a lens dedicated to macro-photography (Nikon 105 mm f/2.8, reproduction ratio 1:1). This ratio means that the size of the image on the sensor is identical to the size of the captured object. The lens is equipped with four synchronized speed-light flash system designed especially for macro-photography. The camera is mounted on a tripod and is set to be perpendicular to the glazing. To guarantee the 1:1 reproduction ratio, the glazing must be at the minimum focus distance from the camera, i.e. 314 mm from the sensor. Hence, a micrometric positioning sliding plate is used to position precisely the camera (Figure 1b).

2.3. Experimental protocol

A full test includes a preliminary transient phase, which is needed to reach the initial steady conditions, and the test phase during which the condensation occurs.

During the preliminary transient phase, we adjust the set points to reproduce winter conditions: cold temperature in the climatic chamber and hot air supply. The humidity content of the supplied air is sufficiently low to avoid condensation. Three days are required to reach stable initial conditions.

At the beginning of the test phase, we increase the humidity set-point for the supply air, and we start recording pictures with the DSLR. The acquisition time step for the DSLR camera is fixed at 60 seconds. Concerning the indoor air metrology, the mobile robot is set up close to the glazing in order to record the evolution of the air velocity, temperature and humidity over time. The data recording time step is set at 60 seconds.
3. Methodology for the condensation rate quantification

From the image series of condensed droplets on the glazing surface, the post-treatment aims to determine the condensation rate using computerized image processing techniques. The experimental data obtained will be compared with theoretical results issued from two analytical models found in the literature.

![Figure 2. Contact angle and droplet radius.](image)

To determine experimentally the condensation rate, for each image taken, we need to evaluate the total mass of water vapor condensed on the glazing surface. This total mass, which is the sum of the droplet mass on this area, can be expressed as follows (Figure 2):

\[
m_{\text{tot}} = \sum m_d = \rho_w \sum V_d = \rho_w \sum \frac{\pi r_d^3}{3} (2 \cos \theta + \cos^3 \theta)
\]

where \(\rho_w [\text{kg/m}^3]\) is the water density at the atmospheric pressure, \(V_d [\text{m}^3]\) is the volume of a droplet, \(r_d [\text{m}]\) is the droplet radius and \(\theta [^\circ]\) is the contact angle between the droplet and the glazing.

Since the contact angle \(\theta\) does not depend on the experimental conditions, it was measured separately. For this evaluation, we used a sample of the glazing installed in MINIBAT. The contact angle was computed using the “half-angle method” [8]. These procedures were repeated several times to determine an averaged value of the contact angle.

The radius of the droplet \(r_d\) can be determined as follows:

\[
r_d = \frac{r_{\text{deq}}}{\sin \theta} = \frac{1}{\sin \theta} \sqrt{\frac{S_d}{\pi}}
\]

where \(r_{\text{deq}} [\text{m}]\) is the equivalent radius and \(S_d [\text{m}^2]\) is the contour area of the droplet.

The condensation pictures capture only the footprint of the droplet, i.e. the shape of the area in which the droplet is in contact with the glazing surface. For an ideal droplet, the footprint is a disk with the radius \(r_{\text{deq}}\). The droplets do not have exactly the shape of a perfect truncated sphere because of the droplet merging. Nevertheless, assuming that Equations (1) and (2) are still valid, the droplets contour area and droplets radius can be determined using computerized image processing techniques.

![Figure 3. Image processing steps for droplets contours finding.](image)

The glazing area being captured by the camera has the dimension of the camera image sensor, which is 35.9 × 24.0 mm. Here we present a cropped and zoomed area of 5.0 × 5.0 mm (Figure 3) for illustration purpose. The image processing method is based on Python environment, along with the OpenCV package for Python. It consists of successive steps to transform and analyse the image to find the droplet contours and to assess the droplets total volume (Figure 3):

1. Histogram equalization: adjusts the image global contrast. This step is useful when the usable data of the image is represented by close contrast values [10];
2. Noise filtering: reduces the noise content, which could potentially be detected later as droplets edges. Since high frequency contents comprise both edges and noises, a simple Gaussian low-pass filter would helping removing noises but also undesirably blurring the edges. Hence, the bilateral filtering is employed [11];
(3) Image thresholding: reduces grayscale images into binary images, i.e. images having only two levels: black and white. This process is essential for increasing the accuracy of the next step. There are several methods for “thresholding” an image. The simplest one is to assign an unique “user-defined” value as threshold value for the whole image - the “Global Thresholding”. When the illuminating conditions vary from an image to another, an adaptive thresholding method might be more relevant; for this, the threshold value is calculated locally for small regions of the image while taking into account the neighbourhood region [12].

(4) Contour finding: consists in finding all the possible contours in the given image. Once these contours retrieved, the following information can be extracted: the number of contours detected that correspond to the total number of droplets; the area and the equivalent radius of each droplet. On the other hand, the condensation rate of droplets can be determined analytically knowing the overall heat transfer coefficient during the condensation process. Two theoretical models are found in the literature: the Griffith’s correlation [13] (as mentioned by [14]) and the Kim’s equation [15]. They will not be described in order to not overload the paper. Details on the two models can be found in their corresponding publications [14, 15] and in [8].

4. Results and discussions
Five tests have been undertaken to ensure the reproducibility of the measurement results. In the present paper, we detail only one test, whose condensation test period lasts for 3 hours. The experimental conditions (wall temperatures, air supply parameters) are summarized in the table 1.

|                    | Ceiling | Floor | S  | N  | E  | W  | Q0  | T0  | r0  | RH0 |
|--------------------|---------|-------|----|----|----|----|-----|-----|-----|-----|
| Initial condition  | 21.4    | 21.1  | 14.2| 21.3| 21.1| 21.1| 150.0| 28.00| 9.06 | 38.6 |
| Test condition     | 21.5    | 21.1  | 15.2| 21.4| 21.1| 21.2| 150.0| 28.01| 14.07| 59.5 |

Figure 4. Condensation growth mechanism.

4.1. Condensation growth mechanism
During the test period, a series of 180 images are captured. Figure 4 presents some relevant images that clearly show the formation, the growth, the coalescence, the fall-off and the re-nucleation of droplets along the glazing. In the beginning (t = 0), droplets form at nucleation sites at the same time, with a very small initial radius. Their size is so small that the camera is not able to do an object-focus properly. As
a result, the vignetting effect (darker zone at the image periphery) can be observed. At this early stage, the droplets grow mainly by direct deposition of condensed saturated vapor onto the glazing surface. At time \( t = 15 \) min (Figure 4b), the DSLR starts to perform a proper focus, as the droplets edges are clearly defined on the pictures. For this reason, this is also the moment for which the image series are used for post-processing. As the droplets become larger in size and as the distances between neighboring droplets become smaller, the coalescence effect begins. Smaller droplets fuse into bigger droplets. The coalescence process appears to be the dominating mechanism for the droplet growth since it lasts from \( t = 15 \) min up until \( t = 171 \) min (from Figure 4b to Figure 4h), which means about two hours and a half. Once the droplets reach a certain size, called "fall-off size", they roll off on the glazing surface. In fact, as the droplets grow by coalescence and reach the “fall-off size”, the gravity forces exceed the capillary force within the droplets. They cause them to fall and sweep away other droplets in their path as can be seen at the moment \( t = 172 \) min (Figure 4i). Just one minute later, right at the freshly cleared glazing surface, new droplets form rapidly at the nucleation sites. The re-nucleation starts over and the growth cycle repeats, next to the other droplets that still undergo the coalescence process (Figure 4j and 4k).

4.2. Condensation rate quantification

Results on the condensation rate obtained from the two theoretical models and from the experimental data are given in Figure 5. The condensation rate obtained from the Kim’s theoretical equation is twice higher than that obtained from the Griffith’s correlation. In fact, the latter depends only on the dew point temperature while the Kim’s model is a more completed equation that depends on the droplet size distribution and the droplet contact angle. The comparison of the experimental results with the Kim’s theoretical equation indicates a mean relative difference of approximately 18%, which implies an overall good agreement.

Nevertheless, the uncertainty of the experimental data remains to be established as the method proposed in this study may include some error sources. One of the error source lies in the image binarization process. This step is crucial since finding droplet contours is based on binarized images. For one global thresholding method, it might be complicated to choose manually an optimal threshold value for each image. The adaptive thresholding methods are relevant choices for images with varying illumination (as we have done) but these methods require input parameters defined by the users and this may lead to some errors. Other error source is related to the image capturing process. The droplets are illuminated differently depending on their size. The more the droplets increase in size, the more the contour edges of the droplets are illuminated non-uniformly from one direction to another (Figure 4). Regardless of the thresholding method employed, there are still some droplet contours that cannot be properly connected. This has an impact on the precision of the results, as these contours non-connected are not taken into account in the calculation of the condensation rate.

In addition, the condensation rate method proposed here requires the droplet volume or one of the main assumption of our data treatment has been that equation (1) is also valid for droplets whose shape is not a perfect truncated sphere.

Consequently, further investigations are needed in order to clarify all these aspects related to the accuracy of the condensation rate quantification methodology developed in this work.
5. Conclusions

The method proposed in this work has led to promising results concerning the condensation rate quantification on cold glazing within ventilated rooms. Moreover, this study confirms that image processing technique is a reliable method for analysing the condensation process on glazed building elements.

In addition, the experimental results on the surface condensation rate presented in this study can be extremely valuable as there are no similar data in the literature for full-scale room. We also believe that the experimental method developed allows improving the current knowledge on the superficial condensation process. The results from this paper can be also used to validate numerical data obtained from CFD simulation concerning superficial condensation process. In fact, CFD numerical studies are ongoing for such problem, starting from previously developed models [5]. The numerical results obtained, as well as the comparison with experimental data, will be the subject of a future work. Nevertheless, some future work is compulsory to consolidate the findings and extend the analysis based on the experimentally method presented here. For example, in order to improve the accuracy of the results, we suggest the following regarding the experimental apparatus: the whole camera system can be upgraded (the body and the lens, to get a higher resolution and a reproduction ratio greater than 1; the camera lens can be also replaced by a telescope). At the same time, the accuracy of experimental results can be greatly improved by refining the image processing technique. This will be mainly possible due to the continuous and remarkable development of computer science.

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