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Hygrothermal evaluation of a museum storage building based on actual measurements and simulations

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Abstract

Museum storage buildings should be able to provide a considerable stable indoor environment in terms of temperature and relative humidity (RH). To obtain such stable conditions with the lowest possible energy consumption, passive air conditioning is one-way solution. In this paper, indoor environment facilities of a passive museum storage building in Vejle region in Denmark, are investigated. Results demonstrate that the weather conditions of the previous years´ considerably affect the indoor environment of the storage. What is more, concentrated dehumidification is a sufficient technique to maintain RH within acceptable levels. Therefore, renewable energy such us excess wind energy during the night can be utilized.

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Keywords: Museum storage space; Dehumidification; Energy efficiency; Conservation conditions; Airtightness; Moisture buffering.

1. Introduction

Conservation of cultural heritage objects from chemical, mechanical and biological deterioration is of crucial importance. Significant fluctuations of temperature may enhance chemical decay [1,2]. Furthermore, strong variations on both temperature and RH levels may yield to mechanical decay [3], while, high humidity levels results in biological decay [4, 5]. Therefore, the optimal preservation of valuable museum collections requires a

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considerable stable indoor environment in terms of temperature and RH. According to British Standard 5454:2000 temperature and RH within a museum storage or archive have to be almost constant (at a value between 45-60%, 13-16ºC) with minimal tolerances around their set points (5%, 1ºC correspondingly) [6]. To obtain such stable indoor environment, extensive air conditioning has to be implemented, which results in significant amounts of energy consumption. However, another solution is currently being developed, which is called "passive air conditioning" [7]. This concept incorporates sufficient thermal insulation, an extremely airtight building envelope as well as high thermal and hygric inertia of the structure [7]. Yet, auxiliary dehumidification is inevitable in order to mitigate the exterior high humidity levels of Denmark's climate [8]. Nevertheless, it has been found that even with dehumidification, there is a great potential for energy savings, if temperature fluctuates within an annual cycle of 10-15ºC [9]. Dehumidification is applied in Vejle museum storage (Fig. 1a.); however, instead of continuous dehumidification an optimized strategy - "concentrated dehumidification" - in a part of a day has been implemented [6]. Based on this technique, dehumidifiers are able to use renewable energy. Therefore, excess wind energy during the night or solar systems during the day can be implemented [10], transforming the museum storage into a nearly CO_2 neutral building [4].

2. Building description

Four rooms characterize the old storage section (Fig. 1b.): two large halls A, C and two smaller halls B, D. A central corridor, which extends through the whole building (and the new part), divides the larger halls from the two smaller ones, enhancing the accessibility of each storage room.

Regarding the new part of the museum storage (Fig. 1b.), it includes three approximately equal sized storage spaces (E, F, G) and a narrow corridor, which separates the old from the new building. In more detail, the exact areas of each hall as well as the required indoor climate conditions are presented below:

- Hall A, C, D: 1100 m^2, 1100 m^2, 400 m^2, RH: 50% (± 5%), T: 7–18 ºC (wooden objects, paintings);
- Hall B: 400 m^2, 40% (± 5%)RH, 10–18 ºC (archaeological objects);
- Hall E, F, G: 620 m^2, 690 m^2, 480 m^2, RH: 50% (± 5%), T: 7–18 ºC;

The main difference between the old and the new storage facilities is the air tightness of the building envelope. The infiltration of the old repository was estimated to be 0.04 air changes per hour (ACH), while for the new storage, it was found to be 0.01 ACH. Heating or cooling systems were not installed, while concentrated dehumidification is used for six hours in the old, and three hours in the new storage respectively. In total four dehumidifiers are used within the storage (two for each repository), which are connected to a ventilation system used to recirculate the air. It is also worth mentioning that floor of the building is not insulated in order to take advantage of the natural heat of the ground.

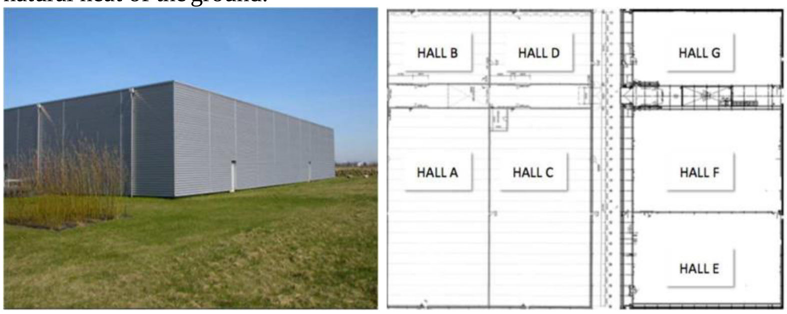


Fig. 1. (a) Exterior view of Vejle's museum storage; (b) Floor plan of old & new storage facilities.

3. Method of investigation

3.1. Building simulations

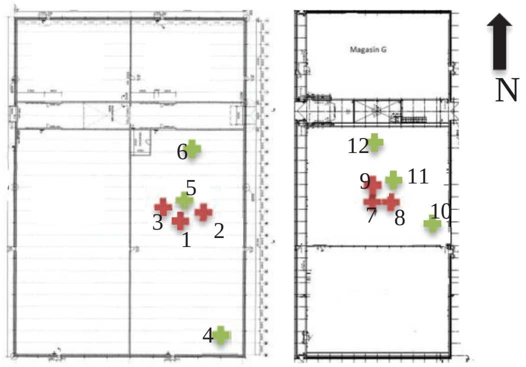
Two building models were used in order to evaluate the indoor climate in terms of indoor air temperature levels. One was developed using the IDA ICE simulation tool, while an already existing model in BSim software was also utilized [7, 10]. An important aspect for both models is the thermal interaction between the interior climate and the volume of soil below the building. The uninsulated floor takes advantage of the natural heat of the ground, which is about 9ºC [11]. Due to the high thermal mass of the soil, ground temperature variations are lower compared to the respective ones of the exterior surface. Thus, ground (soil) acts as a natural source of heat during the winter and as a natural sink for removing heat from the building during the summer. Heat transfer through the ground is a three-dimensional (3D) process [12], while IDA ICE and BSim software considers only one-dimensional (1D) flow. Hence, based on the guidelines of [13] as well as suggestions from UNI EN ISO 13370 [14] standard the 3D heat flow transformed to 1D [8].

The aim of using these models was to compare the outcome of the simulations with actual measurements within the storage facilities and explain reasons for possible deviations. To obtain the most accurate results, actual weather data of each year were used. Hence, it would be possible to make the respective comparisons under the same weather conditions. Graphical representation as well as statistical indicators such as: coefficient of determination (R^2), coefficient of variance of the root-mean-square error (CV-RMSE) and the mean absolute error (MAE) were used to examine if deviation between the predicted temperatures and the actual measurements fall within the acceptable tolerances. It should also be stated that the comparisons took place for the period 2006 – 2013.

Both models were simulated for 10 years (each time with the same weather file) in order to achieve a stable indoor climate. Results of the last year (10th year) were used for the respective comparisons. An additional 17-year simulation was performed in BSim software, where the first 10 years, actual weather data of 2006 were used (in order to obtain a stable climate), while after 2006; each year was simulated with the corresponding weather file. Based on this simulation, it would be possible to examine if the predicted temperatures can be improved by taking into account the outdoor weather conditions of the previous years.

3.2. Full scale measurements

In order to assess if concentrated dehumidification is sufficient to maintain stable RH levels, full-scale measurements in different heights (0 cm, 180 cm, 400 cm, above the ground) in the middle of hall C and F as well as in different spots of the same height (180 cm) were conducted. The exact place, where its group of measurements was carried out is presented in Fig. 2. below. It is worth mentioning that the full-scale measurements within the old storage were carried out during March, while a summer month (June) was chosen for new storage respectively. As the indoor climate of the building is not significantly altered, a characteristic day for each period will be presented in the specific analysis.



Old storage
1. 0 cm above the ground
2. 180 cm above the ground
3. 400 cm above the ground
4. South external wall
5. Middle of the room
6. Close to the corridor

New storage

7. 0 cm above the ground
8. 180 cm above the ground
9. 400 cm above the ground
10. East external wall
11. Middle of the room
12. Close to the corridor

Fig. 2. Full scale measurements of RH within the old and new storage facilities.

4. Results

4.1. Indoor air temperature

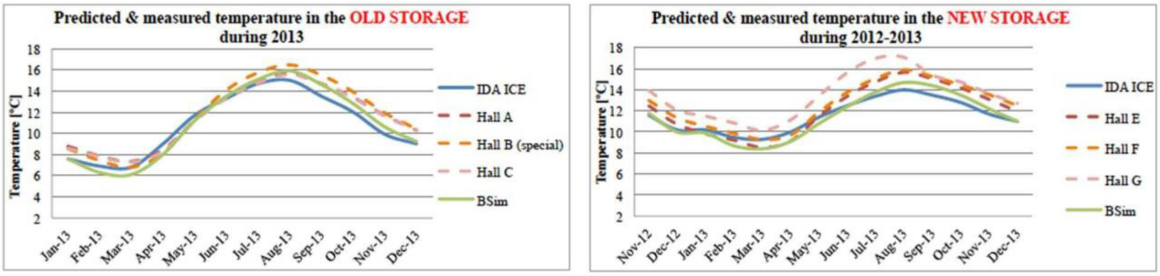


Fig. 3. Confrontation between predicted (IDA ICE, BSim) and measured temperatures for (a) old; (b) new storage, during 2013.

Fig. 3 above exemplifies the respective comparisons during 2013, where the new storage section started its operation. Based on Table 1, it is observed that both IDA ICE and BSim models provide results with a sufficient degree of accuracy, since CV (RMSE) and MAE are lower than 10%. Moreover, it is obvious that BSim predictions (Fig. 3) are “closer” to the real data during the second half of the year and more specifically after the August. This can be explained by the fact that the IDA ICE ground model ISO 13370 failed to take sufficiently into consideration the thermal (time) lag between the outdoor and ground temperature [15]. Maximum outdoor temperature as well as ground temperature occurs during July. However, due to the high thermal capacity of the soil, the highest ground temperature should be observed during October. In such case, ground temperature during winter months would be higher, which in turn will influence the indoor air temperature by increasing it, as the floor is not insulated.

Table 1. R2, CV(RMSE), MAE for IDA ICE and BSim in year 2013.

Old storage	R^2	CV(RMSE) [%]	MAE [%]	**New storage**	R^2	CV(RMSE) [%]	MAE [%]
IDA ICE	0.88	8.62	8.05	**IDA ICE**	0.86	8.29	7.57
BSim	0.94	7.27	6.97	**BSim**	0.94	5.49	4.85

Broadly speaking, during period 2006 - 2013, apart from 2010 it can be concluded that there is a sufficient agreement between the predicted temperatures and the real measurements. Regarding the IDA ICE model, the R^2 varies between 0.86 and 0.93, while results in BSim software show a better agreement (R^2 varies between 0.94 and 0.97). As far as the CV (RMSE) and the MAE are concerned, both models provide results with the respective values to be less than 10%.

According to Fig. 4a, in year 2010 the agreement is far from satisfactory. Both models in IDA ICE and BSim software failed to approximate the real situation, as the predicted temperatures were considerably lower, especially during the first three months. This possibly can be explained by the fact that during 2010, the average outdoor air temperature was notably lower compared to the other years of that period (Table 2). Thus, the lower outdoor temperatures of the 2010 weather file seem to affect the accuracy of the results more than expected.

Table 2. Average outdoor temperatures (2006 -2011).

Year	2006	2007	2008	2009	2010	2011
Average T [ºC]	9.1	9.1	9	8.5	6.5	8.6

For that reason, an additional 17-year simulation was performed in BSim software, where the effect of the weather conditions of the previous years was taken into account. According to Fig 4b, it can be observed that the temperature profile was drastically improved, approaching the actual values. This correction is also reflected in CV

(RMSE) and MAE indicators. Their values were markedly decreased within the acceptable levels (lower than 10%), as it is presented in Table 3.

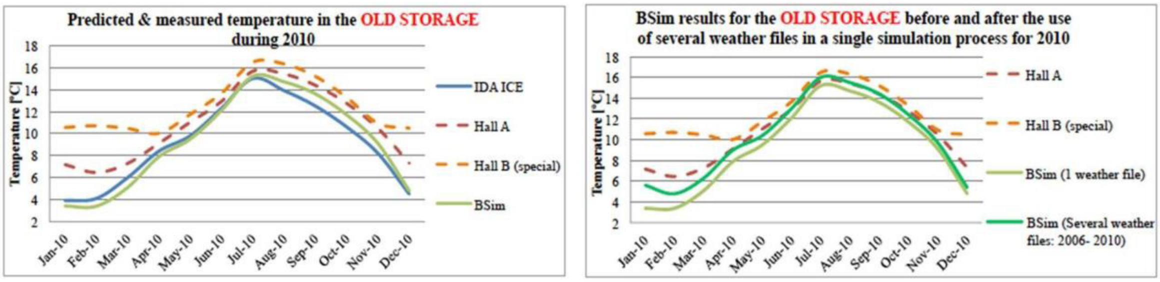


Fig. 4. Confrontation between predicted (IDA ICE, BSim) and measured temperatures based on (a) one; (b) several weather file(s).

Table 3. R2, CV(RMSE), MAE for BSim before and after the use of several weather files.

Year: 2010	R^2	CV(RMSE) [%]	MAE [%]
BSim (1 weather file)	0.75	17.57	19.35
BSim (Several weather files: 2006-2010)	0.93	8.88	8.98

4.2. Relative humidity

Fig. 5 clearly indicates the effect of concentrated dehumidification during the first hours of the day. Dehumidifiers were used from 00:00 to 06:00 every day for the old and 00:00 to 03:00 for the new storage. The remaining hours RH is left "float" without any auxiliary dehumidification.

By calculating the average amplitude of RH, it can be concluded that it is more stable at ground level compared to higher heights (old storage: 0.62% at 0 cm, 0.67% at 180 cm and 0.65% at 400 cm, new storage: 0.57% at 0 cm, 1.06% at 180 cm and 1.61% at 400 cm). This can be explained by the fact that the dehumidifiers are placed in a high spot within the storage. Thereby, the air of higher layers will be first dehumidified. It can also be observed that RH in lower heights (0 cm, 180 cm) in the new storage reaches its lowest value a bit later (around 4:00 am), when the concentrated dehumidification is over. This cannot be observed in the old storage. The specific measurements in the new storage (Hall F) were carried out during June, when outdoor air is more humid compared to March. Moreover, the new storage includes less stored objects compared, fact that indicates lower moisture capacity of the stored mass.

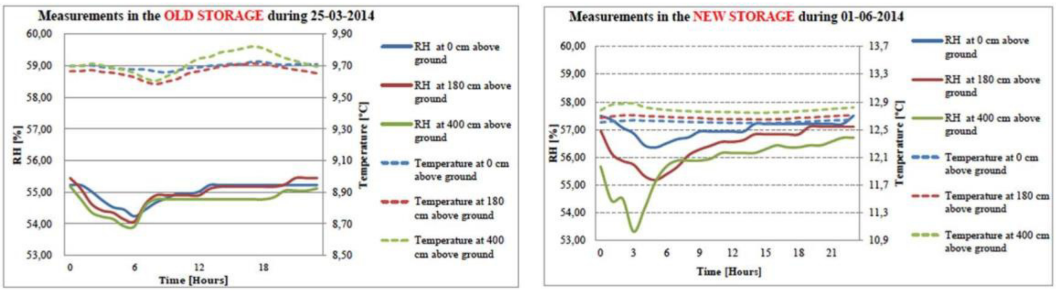


Fig. 5. Full scale measurements of RH in different heights.

Fig. 6 below shows RH fluctuations in different spots within the storage facilities. Regarding the old section, RH is higher close to the south external wall. Hence, the outdoor weather conditions have greater influence close to the external wall of the building. Another possible reason is the dehumidifier's placement.

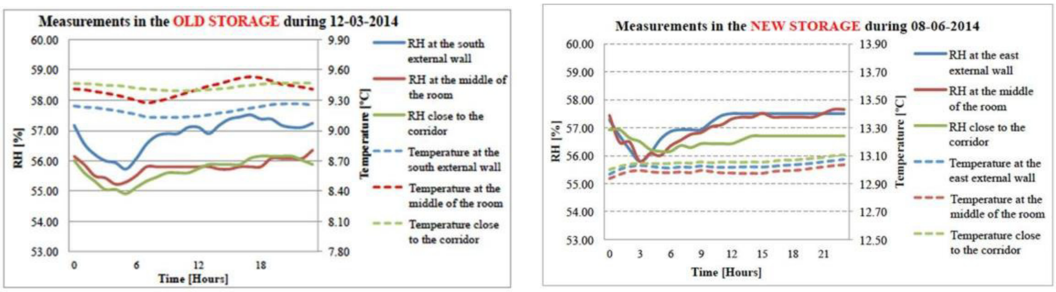


Fig. 6. Full scale measurements of RH in different spots.

It is installed in the back of the room close to the corridor. Therefore, the air of the specific area will be first dehumidified. Regarding the new storage, significant moisture differences were not observed. Thus, the high airtightness, enhance the homogeneity of the indoor environment.

5. Conclusion

Based on the respective analysis it can be concluded that the weather conditions of previous years, affect the indoor environment of the following years. Particularly, taking into account the outdoor weather conditions of the previous years´ significantly decrease the percentage difference of the simulated and measured temperatures. What is more, new dehumidification technique is sufficient to maintain stable relative humidity levels by the end of each day. Hence, dehumidifiers operation can be supplied by renewable energy sources. Concerning the old building part, it seems that lower airtightness affects moisture content in different spots, while dehumidifiers’ placement significantly affects the indoor air consistency.

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