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Simulation of Condensation Problems in a Roller Skating Centre

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The owner of a commercial roller skating centre in southern Australia reported condensation problems on both the roof and floor of his premises. The building is a typical warehouse-type structure with a high level of natural ventilation due to poor construction and permanently open vents. A computer model of the building, using the thermal simulation software TRNSYS, was calibrated from a sensitivity analysis of three key parameters, namely air exchange rate, roof surface heat transfer coefficient and deep ground temperature. The predicted times of condensation on the roof were compared with the owner's observations. The time of year was predicted with acceptable accuracy, although earlier in the morning than had been observed. The effect of installing foil insulation in the roof was simulated. Under normal winter conditions, this modification was enough to stop the condensation. However, in unusually cold and humid conditions, condensation still occurred on both surfaces. This was overcome by heating the floor (15 W/m²) for approximately eight hours. Subsequent modifications by the owner have demonstrated the value of the simulations.

Keywords: Condensation, simulation, TRNSYS, skating centre, warehouse
**Introduction**

Condensation is rarely a positive phenomenon in commercial buildings. Damaged internal finishes, fogged up windows and dripping ceilings are all obviously undesirable and to be avoided. In some buildings, such as the commercial roller skating centre described in this paper, condensation can also be dangerous. Any water on the floor can cause skaters to slip and fall. The outcome would be costly to both the owner and patron and result in bad publicity for the business.

Such a concern caused the owner of a roller skating centre close to Melbourne, Australia, to seek the advice of staff in the School of Architecture and Building at the local university. His questions were straightforward. What was the cause of the condensation and what was an effective and low cost method of eliminating the problem? This paper describes the project initiated by these questions.

**The Problem**

The Rollerway Skate Centre in Geelong is located in a valley near the Barwon River in Victoria. The owner had observed condensation forming on two of the building's internal surfaces at various times of the year. From March to May, condensation could occur on the concrete floor. This was believed to take place at any time between 11am and 5pm. It was thought that this was most likely to occur when several very cold days were followed by a foggy day. From June to August, condensation could occur on the roof of the building, generally between 8am and 9.30am. The condensation on the floor was perceived to be a particular problem
because of the danger it posed to skaters and it meant that the staff was required to dry the floor by hand.

**Initial Diagnosis**

While there are no measurements to assist in the analysis of this condensation problem, the anecdotal evidence of the owner is fairly precise and prompted a number of general and specific observations. This initial diagnosis informed both our investigation and the proposed solutions.

**General Observations**

Condensation is not a regular everyday problem in this building. Condensation on the two surfaces seems to be confined to two separate three-monthly periods. In the case of the floor, condensation occurs only after a specific set of climatic conditions, which are unlikely to occur everyday at that time of year. Any equipment installed to combat the condensation may only be used occasionally, and the owner would probably be reluctant to invest in expensive technology, which remained unused most of the year.

The building is located in a valley near a river, so it is likely that the dew and general moisture levels are higher here than in a normal built environment. The fog reported by the client is almost certainly an example of advection-radiation fog where warm moist air from the river is cooled below its dewpoint by the cooler surrounding land (Bureau of Meteorology, 1977).
**Floor Condensation**

The traditional strategy of increasing the level of ventilation with outside air is unlikely to be effective in overcoming condensation on the floor. When condensation forms on this surface it is probably because the relatively warm late morning/afternoon outside air with raised moisture levels (because of the fog) comes into contact with the cold floor surface. This has been cooled more than usual because of successive cold days. Introducing more outside air by increased ventilation will only make the problem worse. Only dehumidification or raising the temperature of the floor surface is likely to solve the problem (Wing, 1972).

**Roof Condensation**

Since condensation on the roof does not occur in the night, it indicates that the internally generated moisture from the skaters is not the cause of the problem. Normally, one would expect condensation to take place when the moisture-laden air in the building was cooled below its dewpoint by the roof, in turn cooled by radiation to the night sky. The natural ventilation rates must therefore be sufficiently high at night to replace the moist internal air with cooler outside air containing less moisture.

Since the coldest part of the night is generally around 5-6am, the question arises why the owner is so specific that condensation appears to form between 8am and 9.30am, rather than earlier? One possible explanation is that the humidity level of the outside air is increased because of early morning evaporation of dew and other local moisture. When drawn into the building by the high ventilation rates, it is
cooled below its dewpoint by the cold roof before the sun is high enough to heat this surface above that critical level.

**The Research Approach**

The initial diagnosis provided some insight into the reasons for the condensation problems. While the reasoning for the condensation on the floor is credible, the explanation for the timing of the condensation on the roof is less convincing. The research literature on condensation was therefore reviewed for explanations or clues to its occurrence.

Unfortunately, most of the published studies on condensation e.g. Dutt (1979), Nisson (1984), Trechsel et al. (1985), Galbraith and McLean (1990) and Swinton and Karagiozis (1995) were not relevant to this problem. Respectively, these authors explore the problems of condensation caused by diffusion through vapour barriers, absorption by wooden roof sheathing, air-tight buildings, temperature gradients within walls and vapour diffusion through freshly poured concrete.

The last study (Swinton and Karagiozis, 1995) however, did suggest an appropriate methodology that could be followed to investigate the problem described in this paper. These authors took an existing computer simulation tool and adapted it to investigate the heat and moisture flow in their building elements. Once their hypothesis had been validated, the model was then used to investigate strategies to overcome the problem. A similar methodology was therefore adopted in this project. In summary, this involved calibrating a model of the
existing building to predict the observed hours of condensation as closely as possible. Changes that the owner could make to overcome the condensation would then be demonstrated with further simulations using the modified building model.

The detailed methodology adopted was as follows:

- the occurrence of condensation was simulated using the *known* parameters (dimensions, materials and internal loads) and first estimates of key *unknown* parameters.
- these key unknown parameters were then varied and a series of sensitivity simulations were performed to observe the effect on condensation.
- based on the sensitivity simulations and the relevant literature, the values of the key unknown parameters were finally chosen for the final simulations.
- the times of condensation were then predicted and compared with the times and months of its occurrence, as observed by the client, in order to validate the model.
- two 3-day climatic data periods were then created to investigate the condensation problems in more detail, particularly the effect of modifications to the building to prevent their occurrence.

**Building Description**

The skating centre is approximately 42 metres long by 21 metres wide, with a pitched uninsulated galvanized iron roof. The external outer wall height is approximately 4.5 metres high and the highest point of the roof is 6.0 metres. The floor of the building is a concrete slab. It is believed that the slab is approximately
850 mm thick at one end and 215 mm thick at the other, giving an average slab thickness of 530 mm. The magnitude and variation of its thickness was due to the addition of new layers of concrete at various times. A schematic internal cross-section of the building is shown in Figure 1.

**Figure 1** Schematic internal cross-section of the roller skating centre

Different construction materials have been used for the walls of the building. The entrance to the building (the south wall) is a brick veneer construction. The east wall is made of corrugated iron with a fibro-cement inner surface. The north wall is constructed from concrete blocks, but also adjoins another factory and so is not exposed to solar radiation. The west wall, being a firewall, is made of solid concrete with an inner face of two layers of 16mm thick chipboard.

There are a number of louvre windows on the east wall, covering approximately 7% of the wall area. The windows are covered with very loose fitting curtains, which are
permanently drawn. This means that little solar radiation enters the building through the glazing.

The building is naturally ventilated at several locations. Firstly, the louvre windows are left permanently open. There are also six wind-assisted vents on the roof. Finally, there is a central vent running along the apex, but this is partially obstructed so that only about half of the vent is effective. At the junction of the roof and walls daylight can be seen, indicating that the sealing of the building is very poor.

**Internal Loads**

Apart from the moisture, which enters the building with the outside air, moisture is added by the perspiration of the skaters. The number of skaters varies from 10 to 100. There are skating sessions throughout the week, with morning sessions by appointment and evening sessions generally between 6:30pm and 10:30pm. Some afternoon skating occurs at the weekend. There is no heating system in the building. In addition to the skaters, the only heat source is the lights. There are forty 38-Watt lights operating during skating sessions, except when the 5000-Watt light show is in operation.

**The Model**

The computer simulation tool chosen for this study was TRNSYS. This software, launched over 25 years ago, was developed initially to simulate the thermal performance of a solar house in Colorado (Klein *et al.*, 1975). It is generally recognised as the benchmark program for the dynamic simulation of solar energy
systems and over 20 upgrades of the program have occurred to present version (TRNSYS, 2000). Although the program has always been capable of modelling buildings, this was made significantly easier in 1994 with addition of a user-friendly interface called PREBID. The program is now used worldwide to investigate the thermal performance of buildings and their components, particularly by researchers e.g. Jacovides and Mihalakakou, 1995; Blondeau et al., 1997; Sodec, 1999; Hollmuller and Lachal, 2001.

Model Inputs and Outputs

Numerous data must be supplied in TRNSYS to define the building and while the dimensional and material information is known with some degree of certainty (see above), there is a much greater degree of uncertainty over the value of some other model inputs. Four of these were considered to be influential in the formation of condensation on the roof and floor. In combination with the internal latent load, the air infiltration rate will obviously determine the amount of moisture in the building air, and whether this increases or decreases will depend on outside humidity levels. The temperature of the roofing iron, which is critical in establishing whether condensation will occur on this surface, will be determined by the rates of heat transfer between the roof and the inside and outside air. The degree of air movement across the inside surface of the roof is unknown, and so the value of the internal heat transfer coefficient is quite speculative. The equivalent temperature of the upper air mass i.e. sky temperature will also determine the magnitude of radiant heat losses from the roof, and hence its final temperature. The surface temperature of the floor will determine whether condensation occurs on this surface. Apart from the radiative
and convective exchanges with the other building surfaces and the internal air, heat transfer by conduction between the floor and the ground below the slab will be a determinant in its final temperature. The sensitivity of the predictions of this kind of thermal model to the value of ground sink temperature chosen has been shown previously (Fuller et al., 1987).

Table 1 shows the values of these influential but unknown parameters used in the initial simulation of the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration/natural ventilation rate</td>
<td>3 air changes per hour (ACH)</td>
</tr>
<tr>
<td>Sky temperature</td>
<td>Ambient temperature less 12°C</td>
</tr>
<tr>
<td>Deep ground temperature</td>
<td>Average monthly ambient air temperature for Melbourne</td>
</tr>
<tr>
<td>Roof heat transfer coefficients</td>
<td>11 and 64 kJ/h m² K for internal and external heat transfer coefficients respectively</td>
</tr>
</tbody>
</table>

The climatic data used for the simulations was measured in Melbourne, the capital city of Victoria located approximately 90 kms from Geelong. The hourly data is available in the form of a Typical Meteorological Year (TMY), as defined by Duffie and Beckman (1991). Anecdotally, most people believe that the climates of Melbourne and Geelong are very similar, the only difference being the timing of the occurrence of the weather. This depends on the direction and velocity of prevailing winds.
The number of hours at which condensation was predicted to occur on the roof and floor were determined from the model's output. In each case, condensation was deemed to occur when the respective surface temperature falls below the dewpoint temperature of the building air.

Having established the value of the output variables for the initial case, three of the key parameters, namely infiltration rate (ACH), internal roof heat transfer coefficient and deep ground temperature, were then varied to examine their effect on the initial predictions of the number of hours of condensation. In each case, the other key variables were maintained at the initial level. The chosen value of sky temperature, however, was not varied because although algorithms are available to predict sky temperature more accurately using a combination of ambient temperature and cloud cover e.g. Idso and Jackson (1968) and Cole (1976), this was not considered warranted. The average hourly cloud cover value over the year for the data set used is 4.8 octas i.e. close enough to the mean of the possible values (0-8). Although sky temperatures in inland Australia can be as much as 20°C below ambient on cloudless nights (Dunkle et al. 1979), 12°C below ambient is generally considered to be an acceptable average estimate.

Figures 2, 3 and 4 therefore show the effect of increasing ACH, inner roof surface heat transfer coefficient and deep ground temperature respectively. Figure 2 indicates that increasing the value of ACH has a strong effect in reducing the number of hours of condensation on both the floor and roof surfaces, particularly
on the former. In the latter case, however, the effect is diminishing and by about 20 ACH there is only a small effect.

**Figure 2 Effect of ACH on condensation occurrence**

Figure 3 shows that while increasing the inner surface heat transfer coefficient reduces the number of hours of condensation forming on the roof, its effect on the floor is almost negligible. This result is as expected. The gradual increase in deep ground temperature, however, has a strong effect on the number of hours that condensation forms on the floor (Figure 4). If the estimate of deep ground temperature is just 3-4 degrees above the monthly average ambient, then hours of condensation are reduced to zero. The higher temperature of the floor also increases the roof inner surface temperature and consequently reduces the number of hours of condensation on that surface too.
Figure 3 Effect of increased heat transfer coefficient on condensation occurrence

Figure 4 Effect of increased deep ground temperature on condensation occurrence
Revised Parameter Values

Using the knowledge obtained from the sensitivity analysis and the available literature, revised values of the three key parameters were chosen. These values would then be used in a final simulation, the results of which would be compared with the building owner's observations, enabling us to evaluate whether the first objective had been achieved. The chosen values and the accompanying rationale are given below.

Infiltration Rate

Most buildings have a relatively low infiltration rate i.e. 1-3 ACH compared to that achieved by natural or forced ventilation. In this instance, the building is poorly constructed, as evidenced by the gaps at the tops of the walls, so infiltration rates will be high. In addition, the building has six wind assisted vents plus a roof ventilator and permanently open louvre windows to promote natural ventilation, so the effective ACH will be considerably higher.

The infiltration/natural ventilation rate in a building is a function of pressure differences caused by the wind and the stack effect due to temperature differences between the indoor and outdoor air. Although theoretically these factors can be evaluated, ASHRAE (1997) acknowledges that in practice the necessary inputs are difficult to obtain, except in either very simple structures or extremely well studied buildings.
Unlike residential buildings, there is little available literature relevant to this type of building. Perhaps due to their simplicity and "ordinariness", warehouses seem to have attracted little attention from researchers, despite their widespread existence. Synder (1986) observed that "metal building" accounted for over 50% of all low-rise construction in the USA. ASHRAE (1999), however, devotes less than half a page to this type of building, while Jakeman (1981) contains only qualitative statements about the air exchange rate levels that can occur in warehouses, stating that they "often have a grossly excessive infiltration rate…".

The infiltration/natural ventilation rates of greenhouses, which are essentially glazed warehouses, however, have received much more attention, because of the importance of cooling, air movement and carbon dioxide replacement for good plant growth. Some indication of the levels of natural ventilation that might occur can be obtained from this literature. Whittle and Lawrence (1960), for example, measured air exchange rates of between 8.6 and 45 per hour in a greenhouse with a ridge height of 5.5 m, depending on windspeed and the extent of roof and side ventilator openings. Care of course must be taken in comparing the thermal behaviour of glazed and unglazed structures because the stack effect in the former can be large due to the direct capture of solar radiation. However, Jakeman (1981) shows that large temperature gradients of nearly $20^\circ$C can also exist in warehouses with a 6 m ceiling height. The stack effect caused by thermal buoyancy, it should be remembered, will only be dominant in low windspeeds (Baptista et al., 1999).
On the basis of the above and the sensitivity simulations, a fixed level of 20 air changes per hour (ACH) was chosen as the value of infiltration/natural ventilation and was used in all subsequent simulations.

**Roof Heat Transfer Coefficients**

The default value of 11 kJ/h m² K used in TRNSYS is probably a reasonable value for the convective heat transfer coefficient at the inside surface of the roof. Markus and Morris (1980) suggest that 15 and 6 kJ/h m² K should be used for heat flow upwards and downwards respectively. However, in this case due the slope of the roof (approximately 8°) and the suspected higher level of natural air movement through the roof ventilator, it is reasonable to think that the heat transfer coefficient between the building air and the inner surface of the roof should be increased. Accordingly, the TRNSYS default value was therefore doubled to 22 kJ/h m² K in all subsequent calculations.

The external value of heat transfer coefficient is wind dependent, and since the average windspeed for the data set used is 2.9 m/s, the default value of 64 kJ/h m² K was considered to be a reasonable value to use and left unchanged.

**Deep Ground Temperature**

In practice, the floor of the building will lose/gain heat by conduction to the soil at some deep ground temperature and by a combination of conduction and convection from the edges of the slab. Depending on the depth, this deep ground temperature is usually assumed to be some function of the long-term average
ambient air temperature, while edge losses are more closely related to the prevailing ambient air temperature. A detailed procedure for calculating the ground temperature at specific depths and locations in Australia is given by Baggs et al. (1985).

Unfortunately, this work is based on measurements in bare ground, and although there are equation modifiers for vegetation cover and soil diffusivity, there is no discussion about the effects of concrete and bitumen i.e. the deep ground temperature in the urban environment. Adjali et al. (2000) state that the soil temperature at 10 m below their building was 3°C greater than the average external air temperature and that this "provides further evidence of the unsuitability of placing an average external temperature as the deep ground boundary."

Since condensation only occurs on the floor under abnormal weather conditions, it is assumed that under "typical" conditions i.e. those represented by the TMY data file, there will be no condensation. Accordingly, in the final simulations, the deep ground temperature was taken to be the average monthly air temperature for Melbourne but increased by 2°C. This increase effectively calibrated the model to predict almost zero condensation on the floor under typical conditions.

**Simulation Results and Discussion**

Using the key parameters given above, the thermal performance of the building was again predicted. The conditions when condensation would occur on the roof
totalled 169 hours, with only three hours of occurrence of condensation on the floor. A breakdown of the months of the year and times of the day when the condensation occurred on the roof are shown in Figures 5 and 6 respectively.

**Figure 5 Number of hours of roof condensation in each month**

![Bar chart showing hours of roof condensation in each month](image)

Just over half of the condensation on the roof is predicted to occur during the winter months (June-August). These were the problematic months reported by the client. If this period is widened to include September, then about 70% of condensation occurs as reported. It should be noted that the total occurrences of condensation only represent 2% of the total time. This concurs with the reported level of the problem i.e. that it is an occasional, rather than an everyday event.

Figure 5 does, however, point to some interesting anomalies. Condensation occurrences fall sharply in the month of August, but rise again sharply in
September. February, normally the warmest month of the year, has the fourth highest occurrence of condensation. While these observations may be counter-intuitive, it does indicate that the conditions for condensation - cold roofs and moist air - are difficult to predict.

Figure 6 shows that the early hours of the morning were by far the most likely time for condensation to occur. Although this would be as expected under normal circumstances i.e. when the roof surface was at its coldest because of radiation losses to the cold night sky, it does not agree with the observations made by the building owner. He reported that the most prevalent time was between 8am and 9.30am. Figure 6 shows that while 6am is the most likely hour of condensation, the rising sun warms the roof and prevents further occurrence. Closer inspection of the results does show that the days when condensation was still occurring at 8am and 9am did occur in June and July i.e. the reported months. However, this was a continuation of the condensation process that began earlier in the morning rather than exclusively occurring at those particular hours.

**Figure 6 Time of occurrence of roof condensation**
Solutions to the Problem

Although the model falls short of accurately predicting the actual time of occurrence of condensation, it was felt that there was sufficient agreement to use the model to investigate possible solutions. The two condensation problems were investigated separately.

Three successive cold days in July were chosen to investigate the condensation problem on the roof and the relevant temperatures were predicted. Condensation is observed to occur\(^1\) on the roof each morning between the hours of 1am and 10am, as well as a brief period during the evening of the second day (Figure 7). No condensation is predicted to occur on the floor. The effect of installing reflective foil insulation on the underside of roof was then simulated (Figure 8). The predicted foil surface temperatures indicate that these will be above the dewpoint temperature during the entire period, theoretically preventing condensation from forming on this surface.

The condensation problem on the floor was investigated by creating a special data file. A cold day (June 3) was replicated three times to simulate the "successive" cold days mentioned by the owner. The wet bulb temperatures were increased by 5\% to account for the "foggy" conditions, since the relative humidity in fog is generally near 100\% (Bureau of Meteorology, 1977). Initially, predictions of the relevant temperatures were made with the uninsulated roof (Figure 9). Condensation is predicted to occur on the floor during 37 of the total hours in
seven different periods. These are between the early morning hours and noon, and mid evening until midnight. The continuously humid conditions also promote an (almost) equal number of hours of condensation on the uninsulated roof.

Figure 7 Uninsulated roof, floor and dewpoint temperatures in July

![Figure 7 Uninsulated roof, floor and dewpoint temperatures in July](image1)

Figure 8 Insulated roof, floor and dewpoint temperatures in July

![Figure 8 Insulated roof, floor and dewpoint temperatures in July](image2)

1 In Figures 7-11, condensation can be seen to occur on any occasion where the dewpoint temperature (heavy bold line) rises above either of the two surface temperatures
Assuming that the client would install foil insulation, the effect of this modification during the cold foggy period of weather was simulated. The effect of the modification was to reduce the number of hours of condensation on the floor and roof by 38% and 76% respectively (Figure 10). Condensation still occurred on the floor from early morning up until noon on all days, indicating that a further strategy would be required to overcome the problem under these weather conditions.
The effect of a series of roof mounted radiant heaters (equivalent to 15 W/m²) was simulated by adding an energy gain to the floor surface (Figure 11). The heaters were scheduled to turn "on" at 2am and "off" at 10am i.e. an eight-hour period of operation. All condensation on the floor was eliminated by the heating and all but one hour of roof condensation also disappeared because of the warmer floor.
Client Response

As a result of the simulations and recommendations, the client decided that he would initially only install the reflective foil, and observe the effect of this modification. The foil was installed before the start of last winter (Figure 12). Although a stagnant air gap between the foil and the roofing iron was almost certainly not created at many points on the roof because of the roof structure, the results have been very encouraging. The client reports that the condensation problems on both the floor and roof have been greatly reduced.

Figure 12 View of roller skating centre after installation of foil insulation
Conclusions

A review of the literature revealed that there is little published material relevant to the particular condensation problems investigated in this paper. Both are examples of surface condensation, which occur under specific conditions. The model validated the hypothesis of the floor condensation problem, but the timing of the roof condensation, as observed by the owner, could not be predicted.

The infiltration/natural ventilation rates experienced in warehouse-type buildings could only be estimated using the research on agricultural structures. Although there are models for predicting sub-surface ground temperatures in Australia, these are measured for bare ground, rather than beneath buildings in an urban environment.

The methodology adopted to investigate the problem highlights the need to investigate the sensitivity of results to the assumed variables, the results being particularly sensitive to air exchange rate and deep ground temperature.

Despite these difficulties, it was possible to use the standard version of the simulation program, TRNSYS, to obtain results, which were believable and had reasonable agreement with the observations of the building owner with respect to the time of year. However, despite the high infiltration/natural ventilation rates assumed, condensation still occurred predominantly in the early morning hours, rather than after sunrise, as observed by the owner.
The study, however, demonstrated the value of simulation for problem solving on an existing building. The computer model was able to show the effects of a change to the building fabric and the size and operating strategy of the radiant heating system that should be considered. The results enabled the client to understand the process, the likely solutions and to make a decision on a course of action to remedy his problem.

Acknowledgement

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References


