CONDENSATION IN BELOW GROUND METRO STATIONS

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ABSTRACT

Metro systems with significant water ingress can create conditions where condensation forms on surfaces. This may present safety issues (such as trips, slips, and falls), lead to costly asset degradation and look unsightly for passengers.

Modelling condensation in buildings is well understood, where temperatures change slowly, and air velocities are relatively low. However, modelling condensation formation in a station environment where train driven airflows can cause high air velocities and fast fluctuations in temperatures, presents a greater challenge. This paper demonstrated how 1D modelling can be used to assess the formation of condensation in existing metro stations with significant tunnel water ingress. Using this analysis method, this paper will show that if the leakage cannot be prevented, a heated supply system gives an effective mitigation against condensation.

Keywords: Metro, Condensation, Humidity, Station Ventilation, SES.

1. CONDENSATION IN A METRO STATIONS

Condensation forms when humid air meets cool surfaces. More specifically, it forms when the surface temperature is lower than the dew-point temperature of the air. The dew point temperature can be determined using the following formulae [1] by calculating the vapor pressure of the air, then using an iterative technique to determine the temperature for which the calculated vapor pressure is a saturated vapor pressure.

$$p_v = \frac{p_a g}{f_s(0.62197 + g)}$$

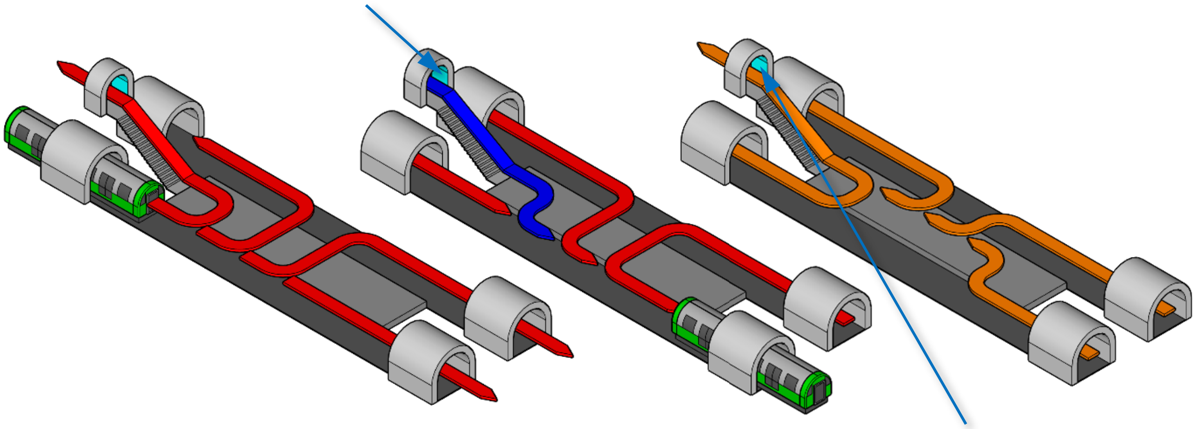
$$\log p_s = 30.59051 - 8.2\log(\theta + 273.16) + 2.4804 \times 10^{-3}(\theta + 273.16) - [3142.31/(\theta + 273.16)]$$

$p_v = vapor\ pressure (kPa)$, $p_a = atmospheric\ (barometric)\ pressure\ (kPa)$,

$g = humidity\ ratio\ (kg/kg)$, $f_s = a\ dimensionless\ enhancement\ factor$,

$p_s = saturated\ vapor\ pressure\ (kPa)$, $\theta = air\ temperature$ (°C)

The humidity of air increases due to the addition on water into the air (thus increasing 'g'). In metros water is added by passengers due to exhalation or sweat, but in our experience, evaporation of seepage water is a key factor in causing condensation. Metro tunnels can run through ground containing a significant amount of water, especially where they run under rivers. This water can seep through the tunnel lining into the tunnel. Older brick-lined and newer immersed tube tunnels can be particularly prone to leakage. This seepage water can create either damp surfaces, standing water or even flowing water along the tunnel. The water ingress, unless channeled, tends to evaporate into the air. The rate of evaporation can be exacerbated if the water is warmed by the tunnel walls, themselves warmed by the long-term accumulation of heat from train operations. The warmer tunnel air also has a higher capacity to hold water. Figure 1 shows three stages in which this water can meet cold surfaces to form condensation.



Cold outside air cools the station exit surfaces.

At night condensation occurs where warm tunnel air meets the cool station exit surfaces.

Figure 1: Train arriving (left), train leaving (middle), night-time with no trains (right).

- In the leftmost pane air from the tunnel is pushed out of the station by the piston effect of an arriving train. This causes warm humid air to encounter cooler surfaces at the upper part of the station.
- In the middle pane the piston effect caused by leaving trains draws cold air into the station, cooling the walls and increasing the propensity for condensation to form.
- In the right pane, during the night (with no piston effect) the warmer tunnel air evaporates the seepage water and increases in moisture content. The warm and humid tunnel air can then rise due to buoyancy and contact colder surfaces forming condensation. Humid air is also less dense than dry air (for example, the molecular mass of water (18 g/mol) is lower than the molecular mass of dry air (29 g/mol) so at a temperature of 15°C, the air density at 50 %RH and 1013.25 hPa is 1.221 kg/m^3; however, at 100 %RH and 1013.25 hPa, it is 1.217 kg/m^3).
- In the morning the process loops back to the left pane. The condensation can become quite pronounced when the trains start operating in the morning as the air leaving the tunnels can be very humid.

While this paper focuses on temperate climates, condensation can occur in tunnel systems in tropical climates as well. For tropical climates, in summer hot and humid air can be drawn into tunnels and encounters surfaces that have been cooled by colder ground conditions.

Condensation manifests as water build-up on surfaces, and if sufficient condensation occurs this water can run off surfaces to affect other areas. In any environment, regular exposure to water where it isn't planned for can cause many issues. Probably the most important impact of condensation is the possibility to increase the number of trips, slips, and falls for passengers and staff. Condensation has been seen to form on tiled walls and floors on stairs leading from platforms, these areas are heavily trafficked and standing water could be a significant hazard. Safety should always be a priority to a metro operator, so reducing or preventing water build-up on walking surfaces should be a primary consideration.

Not all surfaces within a metro station may be designed to handle regular exposure to water, and condensation can form on hidden surfaces. An example could be where steel cladding has been used, and the visible surface has been treated, but the reverse surface has not. In dry conditions, this would not be an issue. However, if humid air could contact both sides of the cladding, condensation could form on the untreated surface causing significant degradation. Furthermore, this degradation would not be visible and could go unnoticed until it has become a much greater problem. This effect on assets could create an increased burden for inspection and maintenance.

Humid air can find its way into any unsealed area and hence there may be the possibility of condensation forming on or close to electrical equipment. This could cause short circuits, damaging equipment, causing service outages, or even presenting a fire risk. If condensation occurs, it is likely that to limit any of the issues discussed, increased cleaning would be required to remove excess water in a station, especially if it was causing issues with passenger and staff safety. This will increase operational costs.

The most obvious mitigation to avoid condensation, to stop the seepage, can be very expensive and difficult, particularly for older structures and tunnels. Compensation grouting can tend to simply move the water ingress to other locations. The next most obvious mitigation would be to increase the extent of overnight ventilation to dilute the humidity. However, some existing railways may not have significant tunnel ventilation facilities, nor much space available to install large plant or create new ventilation shafts to platform level. Direct dehumidification by mechanical or chemical methods can be considered but may be very energy intensive due to the amount of water vapor that would need to be removed.

Our case study is based on an existing metro with little ability to reduce seepage and little tunnel ventilation. We therefore considered mitigations that would take up minimal space and address the two key factors in condensation formation: the reduction in relative humidity in the station and the increase of wall temperatures (to above dew point) in the location where condensation was occurring. Any mitigation would ideally achieve both.

2. ANALYSIS OF CONDENSATION

2.1. General

Evaluation of condensation risk would ideally be built into the analysis of both old and new metros. This would include the ability to estimate or predict how much water flows into the airways; how large the free surfaces areas of any water would be; the temperature and vapor pressure of the water; the undertaking of a mass transfer analogy between convection and evaporative heat exchange, a short time-step simulation capability for all hours of the year, and accurate prediction of wall surface temperatures for complex wall assemblies. At present we do not know of an industry standard way of either accurately and reliability parameterizing the preceding factors into a model a priori, nor a standard tunnel ventilation model that could directly predict the outcomes.

Our experience of dealing with condensation has mainly been in the form of mitigating an existing problem caused by water ingress above and beyond what was foreseen and could be managed. Fortunately, in such cases it is normally possible to obtain measured data to allow better estimates of evaporation rates and wall surface temperatures. If using existing data, as a minimum, air and wall temperature and air humidity data should be obtained over several weeks for the tunnels, outside the station and in the area where condensation is occurring. Furthermore, peak train driven air velocities should be recorded.

2.2. Starting air conditions

The analyses of the risk and mitigations were assessed against what we had observed and measured to be representative starting conditions of 15°C at 95 %RH for the tunnel air conditions at night, 5°C at 70%RH for outside air conditions and station wall/surface temperatures of 11.5°C.

2.3. Starting wall surface temperature

From analysis of recorded temperature data, it was estimated that the wall surface temperatures/local air temperatures at the wall surface in the station were correlated to outside and tunnel air temperatures. For example (as shown in Figure 2) the starting wall surface temperature could be calculated by taking the average of a fixed tunnel air temperature (15°C in this example) and outside air temperature and adding on a factor (in this case 1.5K). For other stations where recorded data was available, similar relationships could be found.

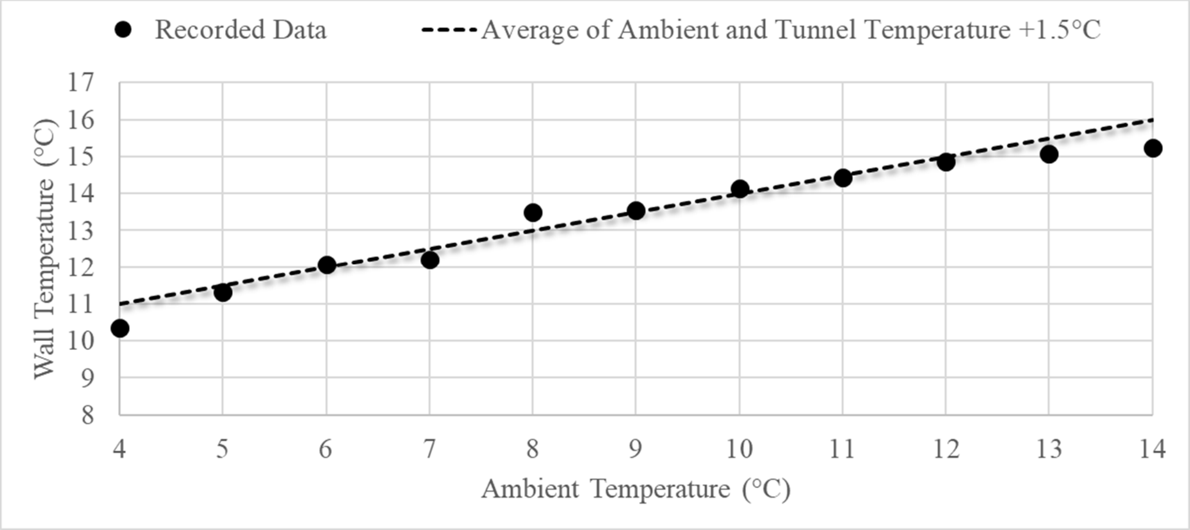


Figure 2: Relationship between ambient air temperature and wall temperature at the area of interest

2.4. 1D analysis to include tunnel airflows

Predicting the air exchange between the tunnels and the station and associated walls was an important part of the analysis. SVS/SES (a well-known and validated one-dimensional model) was used to predict the transport of tunnel air temperatures, humidities, and airflow [2,3,4,5].

By modelling the station and tunnel geometry, along with train movements and initial conditions, we could predict the fluctuations in temperature, humidity, and air flow throughout the station for a period including the last few hours of service in the evening, the hours over night where trains were not running and the first few hours of service in the morning.

2.5. 1D analysis of station surface temperatures

While we could have assumed that station surface temperatures would not change much over this relative short period, some of the mitigations relied on warming of the walls at night. Whilst there is strong confidence in the ability of SES to predict tunnel air temperatures, it has lower predictive capability for short-term transients. We therefore also used a one-dimensional numerical solver, Dynamo, that is specialized in transient tunnel wall heat transfer calculations to model how the station surface temperatures may change over the period where no trains were running. Dynamo was developed by WSP to aid in complex ground/tunnel air transient heat exchange problems. It has been well validated against exact analytical solutions to cyclic transient heat transfer and used by WSP in several applications [6,7,8,9].

2.6. Methodology

The overall process used was to:

1. Place the far-field (tunnel and outside conditions) at the SES model boundaries and use this to calculate the bulk thermal conditions and airflows, including the airflows caused by piston effect, buoyancy, and the additions of any fans.
2. Initialize a Dynamo model representing the station walls between the outside and the tunnels and use this model to calculate second-by second wall and air temperatures and humidities.
3. Use the results of the first two steps in spreadsheets along with the Chartered Institution of Building Services Engineers (CIBSE) formulae to predict dewpoint and evaluate the condensation risk.

Four key cases were analyzed:

1. Base case to verify measured condensation formation could be replicated.
2. Use of exhaust fan located at the station upper levels to draw warm tunnel air up through the station to warm the walls before the morning.
3. Use of supply fan located at the station upper levels to stop humid air rising from the tunnels at night and condensing.
4. As above but with heating of the air at the supply fan to also warm the walls.

For the cases with the fans added at the upper level, the station entrance doors were shut at night to be confident that the resulting airflows did not short-circuit directly to outside.

2.7. Base case results

Figure 3 shows these results for the base case. The trains were modelled as stopping at 02:15 and the analysis focused on the overnight to morning period since this was when condensation was most prevalent.

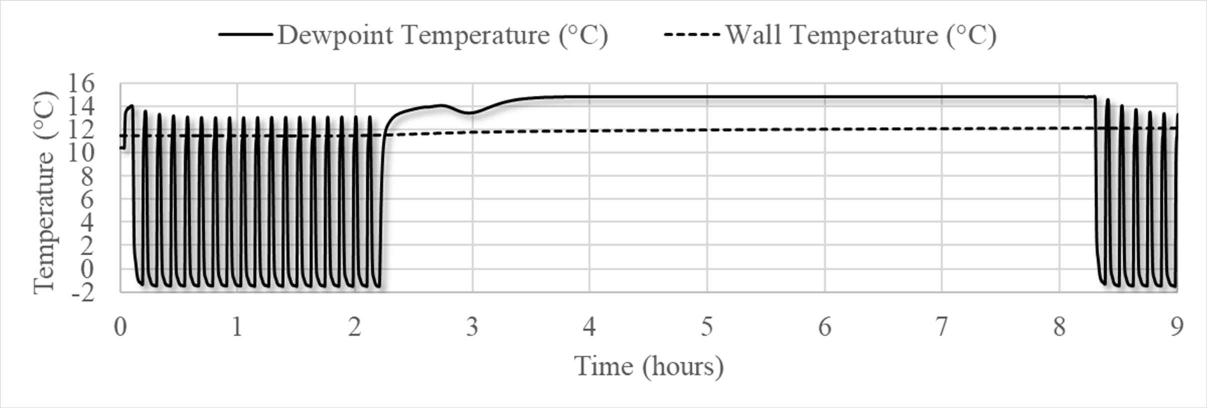


Figure 3: Dewpoint temperature and wall temperature plotted against time for the area of interest

The figure shows that the dewpoint temperature fluctuated during the last few hours of train service as the air is alternately drawn from outside and then pushed from the tunnels. The dewpoint temperature is typically below the wall temperature but for only very short durations and hence condensation is unlikely to form.

During the night, where the trains are not running, the figure shows that the dewpoint temperature rises above the wall temperature and stays there until service resumes in the morning. It is also noted that there is a small rise in wall temperature during this period. During the evening period there was no piston effect to dilute the moisture concentration in the air and hence the still/stagnant air increased in relative humidity due to the seepage coming in from the tunnel walls and floor. Once service resumes in the morning, the dewpoint temperature returns to the same pattern as in the evening reducing the likelihood of condensation forming.

2.8. Mechanical exhaust results

A 5 m³/s fan was adopted drawing air through the station from the tunnels at night. This was a low-capacity fan in recognition of the spatial constraints at the station. The main goal of this mitigation was to see if this could warm the station walls, by virtue of the warmer tunnel air, sufficiently to prevent condensation. Figure 4 shows the analysis results.

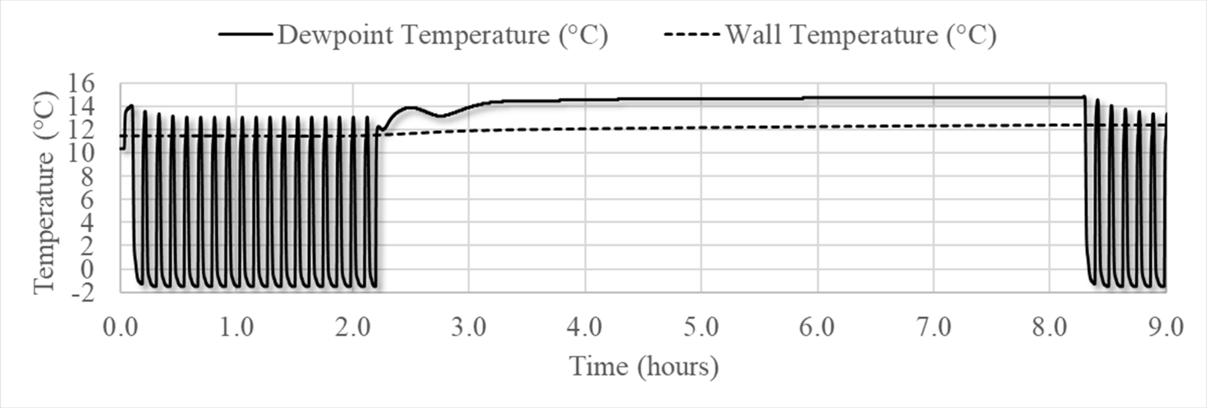


Figure 4: Dewpoint temperature and wall temperature plotted against time for night-time exhaust through station

The station walls were predicted to warm slightly compared to the base case, but not enough to prevent condensation. The temperature rise on the walls was also considered small enough that the cooling effect during the day would cancel it out, so no greater benefit would be seen over several days.

2.9. Mechanical supply results

A 5 m³/s fan supplying outside air through the station at night was assessed to prevent the warm humid air from rising through the station at night and condensing. It was thought that while the air outside may have a high relative humidity, due to its low temperature, it's water content would be low and, therefore, have a dewpoint temperature below the wall temperature. Figure 5 shows the predicted results.

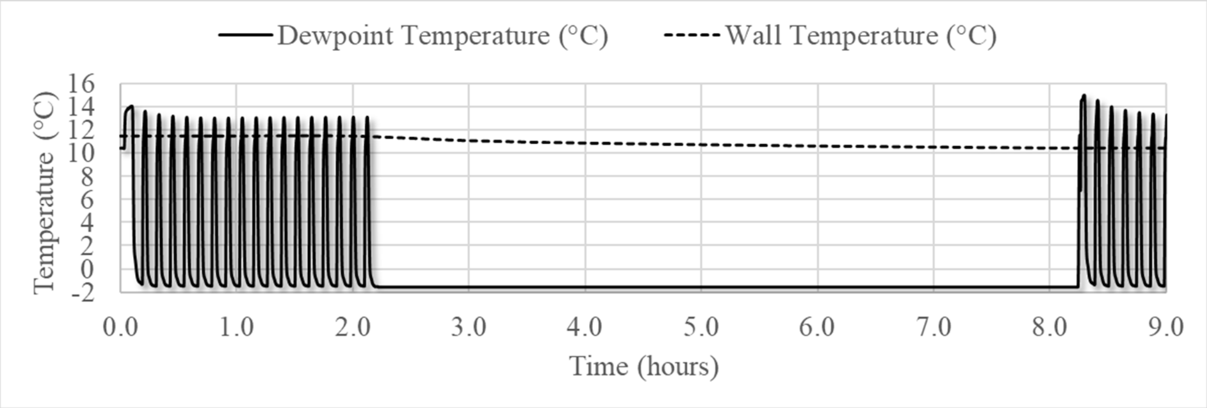


Figure 5: Dewpoint temperature and wall temperature plotted against time for night-time supply through station

Due to the low water content of the cold outside air, the dewpoint temperature is significantly lower than the wall temperature at night, predicting that condensation would be suppressed at night. However, due to the cold temperature of the outside air, the wall temperature was predicted to drop throughout the night, increasing the likelihood of condensation forming first thing in the morning when train service resumed. Spikes of wall temperature below dewpoint temperature can be seen in the right-hand side of the image.

2.10. Heated mechanical supply results

A 2.5 m³/s supply fan was assessed. A heat input of 120 kW was adopted giving a supply temperature at the fan of 45°C. A lower flow rate was used so that a higher air temperature could be achieved for a given heat input (the best permutation of flow and temperature was iterated, but for brevity those results are omitted from the paper). Figure 6 shows the predicted results.

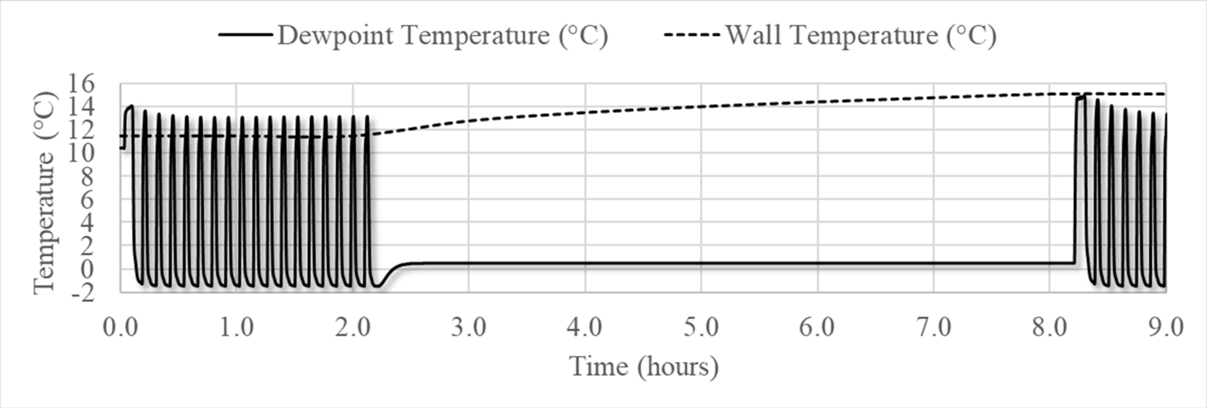


Figure 6: Dewpoint temperature and wall temperature plotted against time for heated night-time supply through station.

The dewpoint temperature of the air in the station during the night was predicted to be much lower than the wall temperature. Furthermore, due to the added heat, the wall temperature was predicted to increases noticeably to the extent that when service resumes in the morning the wall temperature is greater than the predicted air dewpoint temperature. This mitigation, therefore, has the potential to prevent condensation occurring in the morning as well. The control of the heated supply air system requires careful consideration. Ideally the system would be initiated seasonally in advance of cooler periods where condensation is likely. By doing so the walls may be progressively heated, reducing the maximum required capacity of the system.

Clearly this is an energy intensive way of mitigating the issue; however, with an inability to practicably reduce or further channel the seepage, and constraints on airflow capacity, this remains the most practicable alternative. An important factor is to find innovative ways to reduce either the heating capacity and/or energy usage. For example, in tunnels where there is significant seepage water there may also be significant water ingress into sumps. The water temperature may be considerably warmer than the outside air temperature. If this water can be collected and pumped up through the station it could be combined with a water-source heat pump to allow the required heating to be provided with greater energy efficiency.

3. CONCLUSION

By using one dimensional modelling it is possible to predict the formation of condensation within a below ground metro station. Furthermore, it is possible to use these models to predict the effectiveness of possible mitigations against the formation of condensation. However, condensation formation is strongly correlated to the rate of water ingress, and this is very difficult to estimate in advance of construction of any tunnels. Therefore, the use of one-dimensional models will likely rely on some site data and measurements to be valid.

The preferred mitigation for condensation is a little different for tunnels than for general building mitigations, i.e., reduce water ingress and increase ventilation. For this application neither could practicably change. Of the mitigations we assessed, a heated supply system was predicted to be the most effective at minimizing condensation. This was achieved by reducing the dewpoint of the air in the station to below the wall temperature and allowing the heated air to further increase the wall temperature. Heating energy may also be reduced if it is possible to intercept some of the seepage water that is common to such tunnels with condensation issues and using this in combination with a heat pump.

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