A novel algorithm for demand-control of a single-room ventilation unit with a rotary heat exchanger

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ABSTRACT

Energy renovations seek to improve the airtightness of dwellings and thus require ventilation and heat recovery to maintain or improve energy-efficiency, indoor climate, and durability. These ventilation systems often control the indoor air of an apartment as a single climate zone, which neglects the different demands of individual rooms. Renovations result in greater retention of heat and air inside the building envelope, so rooms become especially sensitive to gains from solar radiation, occupancy, moisture loads and pollutants. Single-room ventilation units are able to provide balanced ventilation with heat recovery in individual rooms. This provides a unique opportunity to meet the demands of each room with an appropriate ventilation rate, supply temperature and drying capacity.
In prior publications, the authors described the development of a single-room ventilation unit with a rotary heat exchanger, which is commercially available in Denmark. The unit includes temperature sensors at the inlet and outlet of the supply and exhaust airflows. At the exhaust inlet, a relative humidity sensor is standard and a CO_2 sensor is optional. Together these sensors detect thermal comfort and air quality in the indoor environment. Based on these values, a demand-control algorithm varies fan speeds to change airflow rates and varies the rotational speed of the heat exchanger to modulate heat and moisture recovery. The algorithm varies airflow rates to provide free cooling and limit CO_2 concentrations and varies the coupled heat and moisture recovery to ensure the appropriate supply temperatures for heating or cooling and to modulate drying capacity. In the default setting, the algorithm is not aware of the heating set-point temperature in each room, so the algorithm decides when to bypass heat recovery without compromising efficiency. Moisture control takes higher precedence in the algorithm and overrides temperature and CO_2 controls. In previous publications, the authors demonstrated that modulating regenerative heat recovery could control relative humidities in 'dry rooms', so the algorithm first attempts to limit moisture recovery by varying the rotational speed and then safely unbalances airflows in a worst-case scenario. In the algorithm, frost protection and minimum supply temperature take the highest priority and override other controls. This paper documents the proposed demand control algorithm and analyses its impacts on compliance of building regulations in Denmark. The paper presents an algorithm that manufacturers can program into their controls. The commercially available single-room ventilation unit with a rotary heat exchanger uses this algorithm coded in the C language. Future work will document the effectiveness of the algorithm and how it behaves in a system.

KEYWORDS

Demand-control, Single-room ventilation, Heat recovery, Rotary heat exchanger, Energy renovation

1 INTRODUCTION

Energy renovations seek to improve the airtightness of dwellings and thus require ventilation and heat recovery to maintain or improve energy-efficiency, indoor climate, and durability. These ventilation systems often control the indoor air of an apartment as a single climate zone, which neglects the different demands of individual rooms. Renovations retain heat and air, so rooms become especially sensitive to gains from solar radiation, occupancy, moisture loads and pollutants. Single-room ventilation units may provide balanced ventilation with heat recovery in individual rooms. This provides a unique opportunity to meet the demands of each room with an appropriate ventilation rate, supply temperature and drying capacity.

A single-room ventilation unit may exploit the inherent benefits of decentralization. The cost of exploiting this opportunity decreases with the price of sensors, which has dropped for sensors that detect temperature, humidity and CO_2 concentration. Product developers can combine several of these sensors with a programmable controller to operate as a stand-alone demand-controlled unit with the sensors located at its inlets and outlets. The stand-alone aspect would save costs on electronics for communication but could negatively affect overall system performance. Additionally, the manufacturer could opt for further simplicity and lower costs by providing a very simple user-interface, such as a single button or dial to change the airflow setting. Manufacturers selected this design for the default option of a single-room ventilation unit. Smith and Svendsen (Smith, 2015) described the development of this unit, which is now commercially available in Denmark. The unit employs a rotary heat exchanger, filters, and forward-curved centrifugal fans to deliver balanced airflow and heat recovery greater than 80% at nominal flow. The unit includes temperature sensors at the inlet and outlet of the supply and exhaust airflows. At the exhaust inlet, a relative humidity sensor is standard and a CO_2 sensor is optional. Together these sensors detect thermal comfort and air quality in the indoor environment. Based on these values, a demand-control algorithm modulates airflow via the fan signals and modulates heat and moisture recovery via the rotational speed of the heat exchanger. The occupant selects an airflow from four options, but the demand-control algorithm varies that airflow to provide free cooling and limit CO_2 concentrations. The control algorithm modulates heat recovery to ensure the appropriate supply temperatures for heating or cooling. Since the unit does not include wireless communication by default, the manufacturers opted to develop a wireless hub as an optional add-on. Our investigation uses the default stand-alone product for reference. This paper describes the proposed demand-control algorithm and attempts to justify its architecture. With respect to the algorithm, the paper also comments on design requirements, strengths and weaknesses as well as regulatory compliance in Denmark.

2 ALGORITHM FOR A SINGLE-ROOM UNIT

This investigation focuses on apartments with newly replaced windows, which effectively seal building envelopes. These apartments have low infiltration heat losses and allow greater degrees of control over the ventilation airflows. Figure 1 shows a proposed demand-control strategy for these units. The diamonds represent conditions and the boxes represent processes. The controls should observe the impact of processes before checking subsequent conditions. This observation may include a built-in delay. The figure just provides an example, so implementations should tune these numbers according to context. *T* and *RH* represent temperature and relative humidity respectively, while the subscripts *indoor*, *outdoor* and *supply* describe the location of measurement by the sensors. Additionally, the descriptors *dp, min* and *t-3h* respectively represent dew-point, a prescribed minimum and the time three hours prior. The following sections describe these control modes in detail.

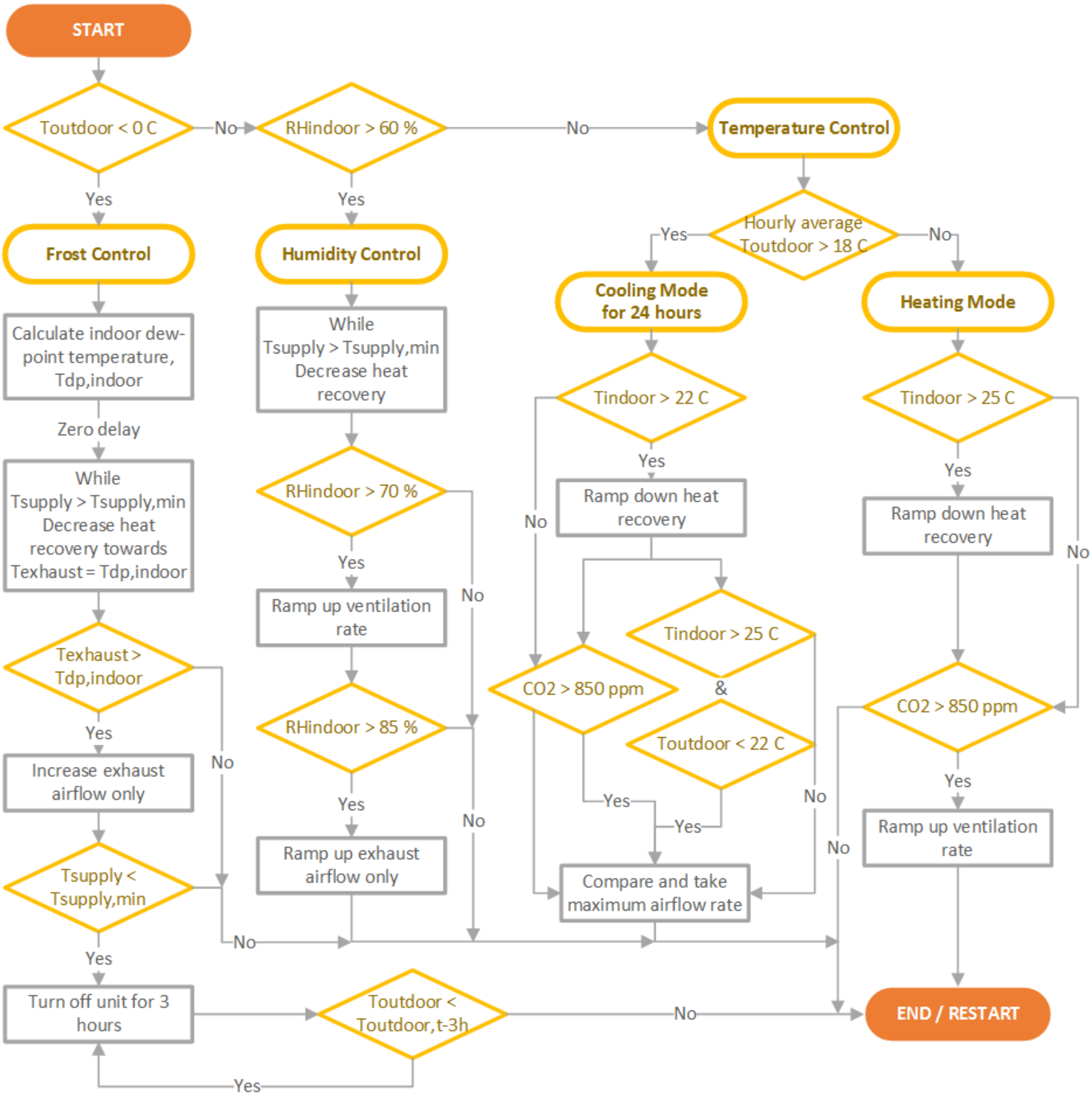

Figure 1. The proposed control algorithm for a single-room ventilation unit with a rotary heat exchanger. The diamonds represent conditions and the boxes represent processes. The controls should observe the impact of processes before checking subsequent conditions.

2.1 Main Temperature Control

During the majority of its operation, the demand-control algorithm for the single-room ventilation unit will use measurements of indoor temperatures and optionally indoor CO_2 concentration. This mode is the *Temperature Control* shown in Figure 1. Not included in the figure is the assumption that the occupant chooses a desired room temperature ($T_{thermostat}$) via a thermostatic radiator valve. The radiator governs the room temperature in typical situations, but improving heat retention reduces the number of hours where heating is necessary. In these hours, the ventilation system will often determine the room temperature. The controls modulate heat recovery to control the room temperature and boost ventilation rates to provide free cooling and prevent over-heating. The occupant can choose to control the room temperature manually by opening and closing windows, but this lacks precision and opens the possibility for wasting heat from radiators. The occupant is less likely to open windows if indoor temperatures remain within their comfort bounds. Berge *et al.* (Berge, 2016) surveyed occupants in high performance residential housing, and the need for cooler air was the dominant reason for keeping the windows open.

In the default stand-alone setting, the ventilation control algorithm lacks knowledge of $T_{thermostat}$ in each room, so the algorithm attempts to modulate heat recovery without compromising efficiency. The ventilation controls must provide full heat recovery up to an assumed set-point temperature (T_{bypass}). If this temperature is too low, the control algorithm will stop using heat recovery and the thermostat will trigger excessive radiator use. The set value of T_{bypass} should be high enough to avoid this situation but not too high that it causes over-heating.

One method to deal with this issue is a conditional set point of T_{bypass}. If there is any risk of over-heating, the algorithm chooses a lower value of T_{bypass} to limit excessive heat recovery. This was the basis for creating a *Heating Mode* and *Cooling Mode*. The algorithm determines the mode based on recent outdoor temperatures. If the average hourly outdoor temperature rises above 18 °C, the algorithm enacts the cooling mode for the next 24 hours. According data from the Danish design reference year by Wang *et al.* (Wang, 2012), the cooling mode would operate during approximately 30% of the year in Denmark, but the algorithm could be adjusted for location. In the example in Figure 1, the heating and cooling modes decrease heat recovery above a T_{bypass} of 25 °C and 22 °C, respectively. In the *Temperature Control* mode, the rest of the algorithm only adjusts ventilation rates.

The cooling mode raises ventilation rates for excessive indoor temperatures, but it first checks for cooling capacity by comparing the indoor and outdoor temperatures. The temperature difference must be greater than 3 °C to warrant boosting the ventilation. Both control modes also boost ventilation rates if an optional CO_2 sensor detects greater than 850 ppm in the indoor air. This value attempts to prevent CO_2 concentrations from rising above 900 ppm, which is the likely limit for category II air quality in the ISO Standard EN 15251 (European Committee for Standardization, 2007). This standard specifies category II as 500 ppm above ambient, which is approximately 400 ppm in much of Denmark. While the cooling control uses a proportional band of 2 °C to increase airflow, the CO_2 control instead attempts to track a reference value, which is 850 ppm in this case. In the cooling mode, the algorithm compares the resultant fan signals based on temperature and CO_2 measurements and delivers the maximum flow. In the heating mode, the CO_2 concentration solely determines the fan signals.

2.2 Moisture Control

Moisture control takes higher precedence in the algorithm and overrides temperature and CO_2 controls. Smith and Svendsen (Smith, 2016) demonstrated that the speed of a rotary heat exchanger could limit relative humidities in 'dry rooms' by limiting condensation on its heat transfer surface. As such, the algorithm first attempts to limit moisture recovery by decreasing rotational speeds between 60% and 70% indoor relative humidity while maintaining sufficient supply temperatures for comfort. The standard EN 15251 also prescribes performance categories to assess indoor relatively humidity, and the upper limits in categories I and III are 50% and 70% respectively. As such, this interval could start as low as 50% to avoid proliferation of dust mites, but the choice is a balance of priorities. Above 70% relative humidity, the algorithm boosts the signal to both fans. A concern with this decision is the moisture content of indoor and outdoor air, where moisture content is the mass of water per mass of dry air. Denmark has a humid temperate climate, so outdoor moisture content could occasionally exceed indoor moisture content and unnecessarily boost fans. The choice to boost fans speeds between 70% and 85% indoor relatively humidity attempts to avoid unnecessary fan power consumption when there is no potential for drying. If the indoor air is 22 °C and has a relative humidity of 70%, then its moisture content is approximately 11.54 g/kg. The outdoor moisture content only exceeds this value for 173 hours in the Danish design reference year. This decreases to 85 hours, 20 hours and 0 hours for indoor relative humidities of 75%, 80%, and 85% respectively. In Denmark, one could regard these durations as acceptable, but one should be aware of this concern and adjust the limits according to climate zone. A more thorough approach would be the inclusion of another humidity sensor to directly compare indoor and outdoor moisture contents, but this presents an added cost. Above 85%, the algorithm safely unbalances airflows in a worst-case scenario. The unbalance of fan signals never exceeds 15% to avoid excessive under-pressure in the apartment. The unbalancing has a compound effect on drying capacity, since it increases both the exhaust airflow and the exhaust temperature (and thereby less condensation), which increases the drying capacity per volume of airflow.

2.3 Freezing Control

In the control algorithm, frost protection and minimum supply temperature take the highest priority and override other controls. In recuperative heat exchangers, it is common to elevate exhaust temperatures above 0 °C in cold climates since condensation only occurs in the exhaust channels of the heat exchanger. This is not possible in a regenerator, such as an uncoated rotary heat exchanger, because condensation on the exhaust side rotates to the supply side, so it will always encounter outdoor temperatures. Therefore, the only method to deal with freezing is to limit condensation from occurring inside the heat exchanger. An algorithm can achieve this with two methods that use feedback control. The first uses a sensor at the exhaust outlet and tracks a relative humidity less than 100% to avoid condensation. Another method uses a temperature and humidity sensor at the point of extraction and calculates the dew-point temperature of the room air. The algorithm ensures that exhaust temperatures do not drop below this dew-point temperature to avoid condensation. The demand-control algorithm in Figure 1 uses the latter method. It was important to the manufacturers of the unit that supply temperatures never drop below a reference point to secure thermal comfort. Therefore, the algorithm restricted the reduction in heat recovery, which may not be sufficient to avoid condensation. Instead, the algorithm only further boosts exhaust airflow and runs unbalanced. As previously mentioned for the moisture control mode, this increases both the supply and exhaust temperatures. If the algorithm still cannot maintain sufficient supply temperatures, the unit shuts down for three hours. It then checks whether outdoor temperatures increased in this three-hour period before resuming operation.

2.4 Variable Heat and Moisture Recovery

The described controls depend heavily on variable heat and moisture recovery to be effective. It may be uncommon to apply variable heat and moisture recovery in this manner, so it deserves further explanation.

The relationship between rotational speed and heat recovery is non-linear with rotary heat exchangers. Smith and Svendsen (Smith, 2015) plotted this relationship for the aforementioned ventilation unit, and Figure 2 shows new measurements with greater resolution. These new measurements used the same method as described by Smith and Svendsen but with a newer version of the unit. The plot only depicts measurements using 40% fan signals for supply and exhaust.

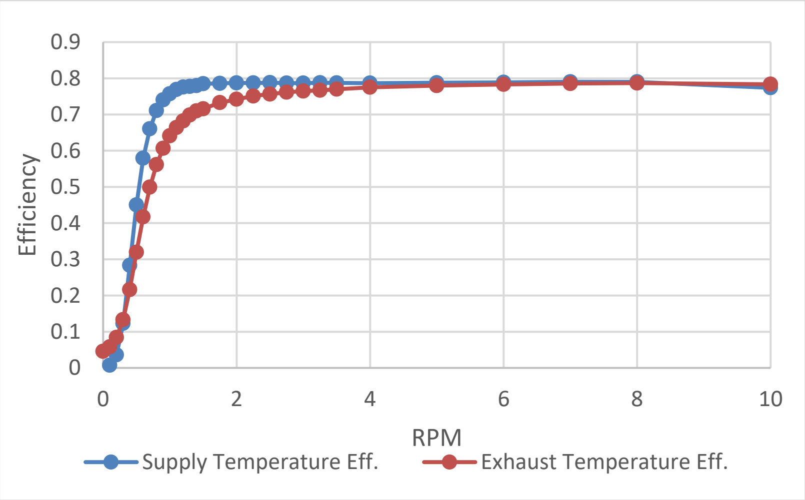

Figure 2. Temperature efficiencies of both the supply and exhaust airflows with various rotational speeds of the rotary heat exchanger in the single-room ventilation unit. The fan signal were 40% for both the supply and exhaust.

Since the relationship between the plotted values is non-linear, it is helpful to create a better gradient for the controls. As the algorithm uses plus-minus control, the impact of each increment or decrement to the rotational speed should be consistent, so the controls will be faster and more stable. The chosen rotational speeds in revolutions per minute for the plus-minus control were 0.0, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 1.0, 1.5, 3.0, and 5.0. Figure 3 shows the supply and exhaust temperature efficiencies at these speeds, and it is clear that they have a more consistent increase across each set of adjacent data-points.

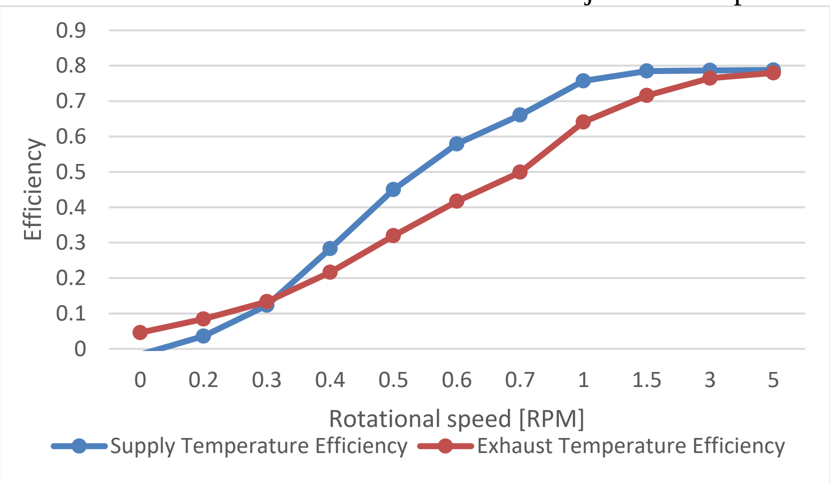

Figure 3. Temperature efficiencies of both the supply and exhaust airflows for various rotational speeds of the rotary heat exchanger. The rotational speeds do not increase linearly in the plot. These were manually selected to improve responsiveness of the controls.

Smith and Svendsen (Smith, 2016) described how an uncoated rotary heat exchanger recovers moisture if there is condensation on its heat transfer surface. That publication provided references and theory to support the claim, but it did not provide any experimental evidence. Table 1 lists the average measurement data for relative humidity, air temperature, dew-point temperature and the calculated moisture content at the inlets and outlets of the supply and exhaust airflows. The ventilation unit used fan signals of 35% and a rotational speed of 10 rpm. The authors described the formula for calculating moisture content based on the three measured quantities in a prior publication (Smith, 2016). Table 2 shows the calculated moisture ratios and temperature efficiencies for the supply and exhaust airflows with the singe-room ventilation unit. The moisture ratios and temperature efficiencies are calculated as the respectively change in moisture or temperature as a percentage of the total potential change during the recovery process. The calculated values include some pressure leakage, which one could also describe as re-circulated air. However, the temperature efficiencies were less than 5% at 0 rpm, as shown in Figure 2, which indicates that very little pressure leakage actually occurred. The authors (Smith, 2015) previously showed analytically that the massflow ratio of pressure leakage to total leakage is equal to the temperature efficiency with a stationary rotor (i.e. 0 rpm). This indicates less than 5% pressure leakage during the measurements. Table 2 shows that the moisture recovery can be equal to or greater than the temperature efficiency at a high indoor temperature and relative humidity. This single measurement supports the assumption that rotary heat exchangers transfer condensation between airflows.

This assumption was also the basis for the controls and moisture balance equations described by Smith and Svendsen (Smith, 2016). The algorithm described in this paper extends that work into a more practical and explicitly defined algorithm.

Table 1. Measurement data for relative humidity (RH), air temperature (T), dep-point temperature (DP) and the calculated moisture content at the inlets (i.e. Indoor and Outdoor) and outlets (i.e. Supply and Exhaust) of the supply and exhaust airflows.

Air Location	RH [%]	T [°C]	DP [°C]	Moisture Content [g/kg]
Supply	78.2	25.6	21.5	0.157
Indoor	72.6	26.9	21.6	0.158
Exhaust	92.0	9.2	8.0	0.066
Outdoor	87.6	7.4	5.5	0.055

Table 2. Calculated moisture ratios and temperature efficiencies for the supply and exhaust airflows with the singe-room ventilation unit. The fan signals were 35% and the heat exchanger rotated at 10 rpm.

Quantity	[%]
Supply Moisture Ratio	100
Exhaust Moisture Ratio	90
Supply Temperature Eff.	93
Exhaust Temperature Eff.	91

2.5 Regulatory Compliance

Building regulations commonly focus on centralised ventilation systems, which supply air to dry rooms (i.e. living rooms and bedrooms) and extract air from wet rooms (i.e. kitchens and bathrooms). Building regulations should explicitly include systems based on single-room ventilation units, but in many cases, the designer of these systems requires extra clarification from regulators. The Danish building regulations (Danish Energy Agency, 2015) state that all habitable rooms, as well as the dwelling as a whole, must have ventilation supply of at least 0.3 L/s/m^2 of heated floor area. This is straightforward for single-room ventilation units, which can be set to supply at least this amount based the floor area of each room. Another provision states that this background airflow must include heat recovery, which single-room units can also satisfy.

The regulations regarding kitchens and bathrooms require more interpretation. A kitchen and bathroom require the capacity to exhaust up to 20 L/s and 15 L/s respectively. There are no regulations for supply, so there is nothing in the text of the building regulations to prevent solutions that use balanced ventilation in each room. One author of the Danish building regulations confirmed this interpretation and noted the restricted spread of moisture from contaminated rooms to other rooms. This is important since the described ventilation unit primarily serves dry rooms, so it should not draw air that is more humid from wet rooms. In the moisture control mode, the unit operates with unbalanced airflows for room relative humidities above 85 %, so it will create an under-pressure in the room that will potentially draw air from other rooms. However, this unbalance is zero at 85 % and grows proportionally with higher relative humidities. This is in the range of maximum relatively humidity, so one could assume that the air in other rooms does not carry significantly more moisture unless it also has a much higher temperature.

The frost control mode in the algorithm also uses unbalanced airflows, and the compliance of this decision is less clear. When outdoor temperatures drop below 0 °C, the controls could have three options to limit frost accumulation. The algorithm could decrease heat recovery to raise the exhaust temperatures above the dew-point temperature of the indoor air. This would avoid condensation and thus freezing in the heat exchanger. However, this could lower supply temperatures below the comfort threshold of the occupant. Another option would be to simultaneously decrease heat recovery and unbalance the ventilation airflows. By increasing the exhaust or decreasing the supply, the algorithm has greater capacity to maintain sufficiently high exhaust temperatures to avoid condensation while also meeting the comfort requirements of the occupant. This is the option applied in the proposed algorithm, but its use of unbalanced airflows may be an issue regarding compliance. The third option is to shut off the unit until temperatures rise above 0 °C, but this does not satisfy the minimum ventilation requirements. It is clear that none of the options is perfect for all situations.

Centralised ventilation systems solve this issue by including a heating coil before or after the heat exchanger on the supply side to satisfy comfort requirements when bypassing heat recovery to avoid freezing. Centralised heating allows the use of a less expensive heat source, such as district heating, but this is not feasible in single-room ventilation units. Electric resistance coils could be an alternative, but the cost of electricity is approximately 5.5 times that of district heating, which prohibits this option. Rather than heat the supply air, it may possible to lower supply temperatures and still ensure reasonable levels of thermal comfort. Until recently, conventional ventilation systems extracted air from kitchens and bathrooms and supplied air through noise dampening inlets in the façade of dry rooms. Even in newer buildings with relatively airtight envelopes, discomfort due to cold draughts is rarely seen as a problem through these inlets. When it is a problem, the solution is to close the inlets and restrict the exhaust. The inlets do not employ fans, so air velocities are low, but there is no control over diffusion or mixing of airflows, which single-room units could apply. If a unit adequately diffuses ventilation airflow to lower velocities and enhances mixing with room air, there could be less concern of draught from cooler supply temperature. This would be the most compliant option. The necessary change to the algorithm in Figure 1 would be the removal of the statement “while $T_{supply} > T_{supply,min}$” and removal of everything from “$T_{exhaust} > T_{dp,indoor}$” onwards. An important consideration here is that lower heat recovery has the effect of increasing drying capacity with rotary heat exchangers. As drying capacity increases, the indoor dew-point temperature likely decreases, which increases the allowable heat recovery to avoid condensation. Therefore, the algorithm will likely find an equilibrium at lower indoor relative humidities and thus lower dew-point temperatures.

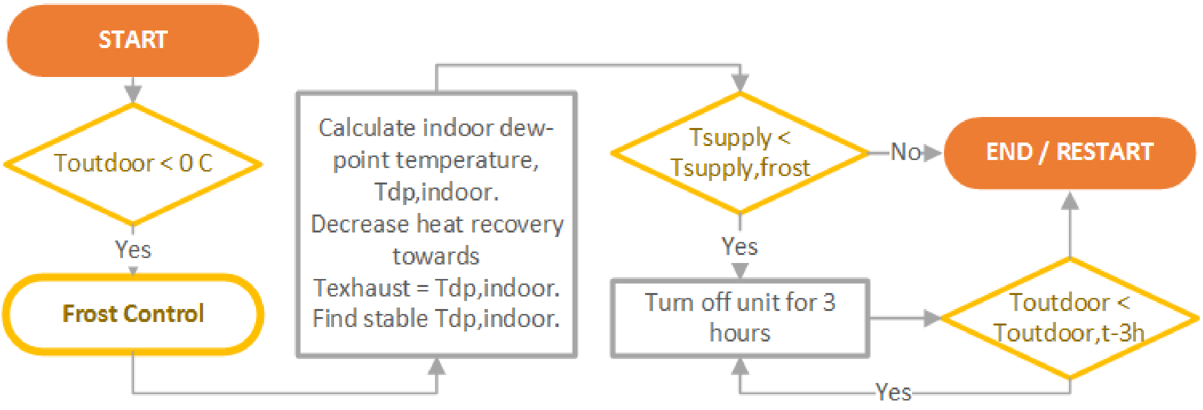

Figure 4. Alternate frost control mode that complies with building regulations but risks causing cool draughts for the occupant. The algorithm introduces a new parameter, $T_{supply,frost}$, which is a lower limit on the minimum supply temperature only in the frost control mode.

3 DISCUSSION

This paper demonstrates that it is possible to construct an algorithm for stand-alone operation of a single-room ventilation unit with a rotary heat exchanger. The algorithm targets a range of thermal comfort without compromising heat recovery. The algorithm also targets a range of indoor relative humidities to prevent mould growth. Despite the inherent coupling of heat and moisture recovery in highly effective uncoated rotary heat exchangers, the algorithm attempts to find a balance that satisfies multiple demands (i.e. energy-efficiency and moisture limits). The algorithm also attempts to avoid frost accumulation in the heat exchanger while satisfying a requirement for minimum supply temperatures imposed by the manufacturer of the unit. This paper acknowledges the consequences of this decision with respect to regulatory compliance and proposes an alternative that would improve compliance. This alternative relaxes the constraints on supply temperatures, but this may not be an issue for appropriate designs of the ventilation diffuser. This decision could follow experimental testing, which would produce a different result with every single-room ventilation unit. This paper therefore covers the breadth of issues facing autonomous control of these units and leaves open questions for individual product developers.

Implementation of the proposed algorithm would be different for all developers of single-room ventilation units with rotary heat exchangers. Much of the text refers to set-point temperatures and relative humidities that depend on the local climate to be effective. These may require tuning. Simulations may assist in finding optimal values, but it is likely that some decisions would require experimental testing. For instance, the decision to restrict minimum supply temperatures could impact regulatory compliance, but this decision is unique for each unit based on the inlet airflow. Regardless, documentation of a full case study would provide useful information, and the authors plan to test the algorithm in full-scale experiments. The authors wrote the algorithm shown in Figure 1 in pseudo-code, and control engineers subsequently translated it into C code for implementation in the commercially available unit. Simulations will accompany these tests and may influence the refinement of set points. This work is all very necessary since there is no evidence yet that the proposed algorithm is actually effective. User behaviour is difficult to predict and may have unforeseen consequences. Furthermore, the planned full-scale experiments will include different forms of kitchen exhaust (i.e. balanced or unbalanced, with or without heat recovery) to assess the impact on heat recovery and supply temperatures in each of the single-room units. No ventilation unit operates in isolation from other pressures, so it is very necessary to study the decentralised unit as part of a system. This future work will target successful ventilation systems that include single-room units.

4 CONCLUSIONS

This paper documents a proposed demand-control algorithm for a single-room ventilation unit with a rotary heat exchanger. The algorithm uses sensors inside the unit to control air quality and thermal comfort according the demands of each room. It aims to achieve this by modulating the supply and exhaust airflows and the rotational speed of the rotary heat exchanger. The algorithm protects against frost accumulation and seeks to modulate coupled heat and moisture recovery to achieve a balance between energy efficiency and avoidance of mould risk. The paper discusses its compliance on building regulations in Denmark. Future work will document the effectiveness of the algorithm and how it will behave in a system.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Berge, M., & Mathisen, H. M. (2016). Perceived and measured indoor climate conditions in high-performance residential buildings. *Energy and Buildings, 127*, 1057–1073. http://doi.org/10.1016/j.enbuild.2016.06.061

European Committee for Standardization (2007). *EN 15251: Criteria for indoor environment including thermal, indoor air quality, light and noise*. Brussels: European Committee for Standardization

Danish Energy Agency (2015). *Danish Building Regulations 2015*. Danish Transport and Construction Agency. http://bygningsreglementet.dk/file/591081/br15_english.pdf

Smith, K. M., & Svendsen, S. (2016). The effect of a rotary heat exchanger in room-based ventilation on indoor humidity in existing apartments in temperate climates. *Energy and Buildings*, *116*, 349–361. http://doi.org/10.1016/j.enbuild.2015.12.025

Smith, K. M., & Svendsen, S. (2015). Development of a plastic rotary heat exchanger for room-based ventilation in existing apartments. *Energy and Buildings, 107*, 1–10. http://doi.org/10.1016/j.enbuild.2015.07.061

Smith, K. M., & Svendsen, S. (2016). Control of Single-room Ventilation with Regenerative Heat Recovery for Indoor Climate and Energy Performance. *Clima 2016 - Proceedings of the 12th Rehva World Congress*.

Wang, P.G., & Scharling, M., Nielsen, K.P. (2012). 2001 – 2010 Design Reference Year for Denmark. *Teknisk Rapport 12-17*. Copenhagen: Danish Meteorological Institute.