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New calculation method to solve moisture balance in the room with regenerator heat recovery and infiltration

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Abstract

This paper investigates moisture related performance of a regenerator heat exchanger located in a decentralized ventilation unit for residential building application. The decentralized ventilation solutions have recently become a more and more popular alternative to centralized ventilation systems. Due to the small space available and in order to avoid maintenance of these types of units, they are equipped with regenerator heat exchanger in some cases. In the recent past and also presently, Building Regulations (BR) and European directives have increased demands for heat recovery efficiency in air handling units (AHUs). In the case of regenerator heat exchanger, the higher the heat recovery efficiency obtained the higher risk that condensation might occur. This condensation might form small droplets on the surface of the regenerator that might not be possible to drain in the short switching time of the regenerator and consequently might be evaporated in the next cycle back to the building and cause elevated humidity conditions in the indoor spaces. Due to the fact that the traditionally used dilution equation must not be used to solve moisture balance in the room with regenerator heat exchanger and infiltration, this paper presents a new calculation methodology that takes into account infiltration, condensation in the regenerator, and back evaporation to the room. The paper compares humidity levels in the room ventilated with regenerator heat exchanger and ordinary counter-flow exchanger. Theoretical calculations indicate that the ability of a ventilation system with regenerator to remove moisture from the room is very dependent on moisture loads in the room, air change rate, and infiltration rate.

Keywords: regenerator heat exchanger; decentralized ventilation; moisture balance, condensation

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Nomenclature

$m_{sources}$	moisture load from people [kg/s]
x_{room}	absolute humidity in the room [kg/kg]
x_{amb}	outdoor air absolute humidity [kg/kg]
x_{cond}	vapour condensation in the regenerator [kg/kg]
x_{sat}	absolute humidity of saturated air [kg/kg]
$x_{aft\ reg}$	absolute humidity of inlet air after passing regenerator [kg/kg]
n_{vent}	air change rate due to ventilation [h^{-1}]
n_{inf}	air change rate due to infiltration[h^{-1}]
ρ	air density [kg/m^3]
V_{room}	room volume [m^3]
t	time [h]
M_{in}	total water vapour in the inlet air (ventilation and infiltration) [kg/h]
M_{out}	total water vapour in the outlet air (ventilation and exfiltration) [kg/h]
m	air mass flow [kg/s]
i	time step

1. Introduction

In the recent past and in the upcoming years, Ecodesign and respective EU countries have increased and will increase the demand for minimum heat recovery in ventilation air handling units (AHU). For example, Euro Parliament directive [2] determines a minimum demand for environmentally friendly design of AHU where one of demands is related to minimum efficiency of heat recovery. Directive set heat recovery of two-way AHUs to be minimum at 73% from 1 January 2018 and refers in the appendix to benchmark value at 85%, which is expected required heat recovery in, for example, in Denmark and Germany in the near future.

Heat recovery can be obtained in several different methods, e.g. in counter flow heat exchangers, cross heat exchangers, rotation heat exchangers and regenerators. They all represent very high heat recovery efficiency, approximately 70 – 90 % which makes them very popular in many AHUs. However, in the decentralized ventilation systems (DVS), some of them have more interesting technology than others. Firstly, in the decentralized systems that are often integrated in the building envelope, the size of the unit has to be small and compact due to very limited space. Secondly, the unit should require minimum maintenance due to a large number of units and consequently a potential high cost of operation. Thirdly, it should be possible to drain the unit from condensation and if condensation occurs then it should not be allowed to freeze. The DVS with regenerator heat exchanger is a very interesting candidate and fulfills most of the criteria: It is compact, does not require maintenance, has no moveable parts, and it will not freeze in case of condensation. The only unsolved issue is related to the risk of evaporation of condensation back to the room and, therefore, this should be investigated.

The well-known dynamic dilution equation Eq. [1] can be applied in its unchanged form for counter-flow heat exchanger and infiltration, and this is due to the fact that absolute humidity of inlet air and ventilation air is the same. The dilution equation must not be applied to calculate the regenerator heat exchanger and infiltration because these two air flows might not have the same absolute humidity due to condensation in the regenerator. If one wants to apply the dilution equation to calculate humidity levels in the room ventilated by the air handling unit AHU with regenerator then must not take into account infiltration. However, this is very serious limitation and results could be, especially in winter, significantly affected by the simplification.

$$x_{room} = \frac{\sum m_{sources}}{M}(1 - e^{-n*1}) + (x_{room} - x_{amb}) * e^{-n*1} + x_{amb} \quad (1)$$

2. Methodology

In this paper proposes the iterative calculation method that allows performing dynamic calculation of moisture content in the room ventilated by AHU with regenerator heat exchanger and, at the same time, takes into account infiltration. Firstly, general mass balance for the room is established, see Eq. 2.

$$\left[m\frac{dx}{dt}\right] = m_{sources}(t) + M_{in}(t) + M_{out}(t) \quad (2)$$

Secondly, mass flows are separated for ventilation air and infiltration air, see Eq. 3.

$$\left[\rho V_{room}\frac{dx}{dt}\right] = m_{sources}(t) + n_{inf}\rho V_{room}[x_{amb}(t) - x_{room}(t)] + n_{vent}(t)\rho V_{room}[x_{sup}(t) - x_{room}(t)] \quad (3)$$

Thirdly, sought parameter, namely room absolute humidity, is separated and iteration is included in the mass balance, see Eq. 4.

$$x_{room,i} = x_{room,i-1} + \frac{m_{sources,i-1}}{(\rho V)_{room}} + n_{inf}(x_{amb,i-1} - \min\{x_{room,i-1}; x_{sat,room}\}) + n_{vent,room}(x_{aft\ reg,i-1} - \min\{x_{room,i-1}; x_{sat,room}\}) \quad (4)$$

The moisture content in the inlet air after regenerator is not necessary equal to the ambient moisture content as it would be for counter-flow exchanger where outlet air and inlet air are tightly separated from each other. In the regenerator heat exchanger, it should be considered that inlet air absolute humidity is the minimum value between the saturated conditions after regenerator and the ambient humidity plus the condensation that occurred in the regenerator in the previous cycle. Absolute humidity of the inlet air after regenerator thus can be calculated using Eq.5 and Eq.6 and then substituted in Eq. 4.

$$x_{cond,i-1} = x_{room,i-1} - x_{sat\ exhaust,i-1} \quad (5)$$

$$x_{aft\ reg,i-1} = \min(x_{sat\ inlet,i-1}; x_{amb,i-1} + x_{cond,i-1}) \quad (6)$$

2.1. Validation of the method

Validation of the proposed moisture balance is performed against the well-established dilution equation. Due to the fact that the dilution equation must not be used for regenerator heat exchanger and infiltration at the same time, validation of the moisture balance is performed for the counter-flow exchanger. The thermodynamic conditions specifying absolute humidity of the inlet air after regenerator in Eqs. 5 and 6 are not substituted in Eq. 4 because absolute humidity of the inlet air after heat exchanger stays unchanged and equal to ambient air humidity (x_{amb}). Except for this single modification, the moisture balance is kept unchanged as presented in Eq. 4.

For counter-flow exchanger above presented balance in Eq. 4 gets form, see Eq. 7:

$$x_{room,i} = x_{room,i-1} + \frac{m_{sources,i-1}}{(\rho V)_{room}} + n_{inf}(x_{amb,i-1} - \min\{x_{room,i-1}; x_{sat,room}\}) + n_{vent,room}(x_{amb,i-1} - \min\{x_{room,i-1}; x_{sat,room}\}) \quad (7)$$

Results are validated by comparing them to results obtained from dilution equation, see Eq. 8.

$$x_{room,i} = \frac{\sum m_{people,i}}{M_i}(1 - e^{-n*1}) + (x_{room.i-1} - x_{amb,i}) * e^{-n*1} + x_{amb,i} \quad (8)$$

Validation is performed using Danish Design Reference Year weather data and assuming the same moisture load and schedule in the room, air change rate for ventilation and infiltration. Fig.1 presents the validation results.

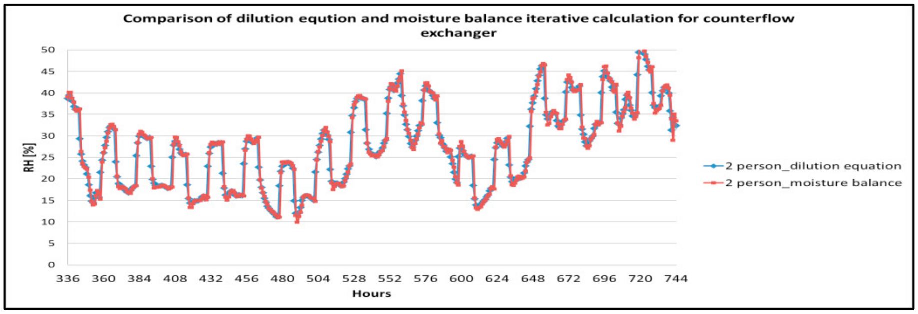

Fig.1. Comparison of results from moisture balance and dilution equation for the chosen period of 2 weeks in January.

Good match was obtained in the validation process of the new balance equation for counter-flow exchanger. The conditions specified in Eqs. 5 and 6 for regenerator exchanger are purely thermodynamic conditions. Their substitution in the balance equation proposed in Eq. 4 do not influence the correctness of the balance and, therefore, it can be stated that if balance is validated for counter-flow exchanger then it is also correct for regenerator exchanger.

3. Results

This chapter presents assumptions behind calculations and results from the conducted study. Several assumptions have been made in order to conduct calculations. Assumptions are chosen in the manner to represent a real life scenario as closely as possible. Decentralized ventilation units usually provides air to only one room and in this study it was assumed that this room would be the bedroom.

Calculation assumptions:

- Moisture load: one sleeping person produces 0,04 [kg H_2O/h]
- Room is occupied from 22 to 7 o'clock (during night) by either 1 person or 2 persons
- Regenerator efficiency is 85 [%]
- Air flow: 25,2 [m^3/h] (constant independently on number of people)
- Infiltration included in the moisture balance is at 0.13 [1/h]
- Outdoor parameters: Hourly values for 1 year, Danish Design Reference Year - DRY-v2.
- Ventilation is running 24/7 (always)
- The geometry of the room is: **Floor area**: 14.3 m^2; **Height**: 2.8 m; **Volume**: 40 m^3

Calculations have been performed hourly for 1 year, but results are presented only for a short winter period, namely two weeks in January when condensation risk is very high. Figs 2 and 3 present results for bedroom with respective moisture load from 1 and 2 persons. Presented in Fig. 1 and 2 results assume that if condensation occurs then all condensation from a previous cycle will evaporate back to the inlet air and consequently back to the room in the following cycle.
In Fig. 1 can be observed that indoor relative humidity for regenerator and counter flow exchanger is kept almost the same. Only single days with slightly elevated relative humidity due to condensation in the regenerator can be observed. In Fig. 2 it is distinct that the condensation in the regenerator might be a reason for significantly higher indoor relative humidity.

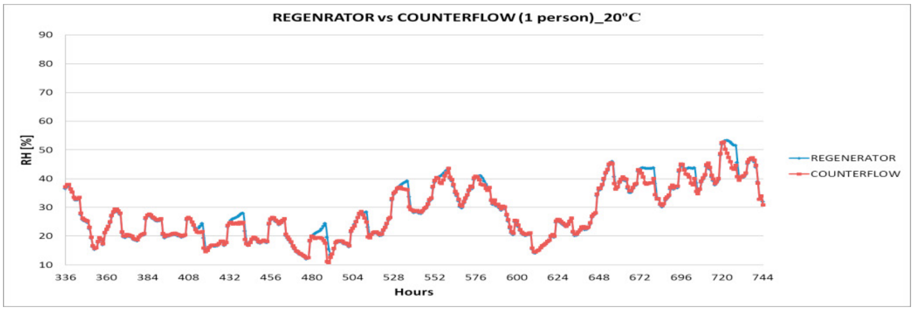

Fig. 2. Room relative humidity calculated for second half of January with 1-person load.

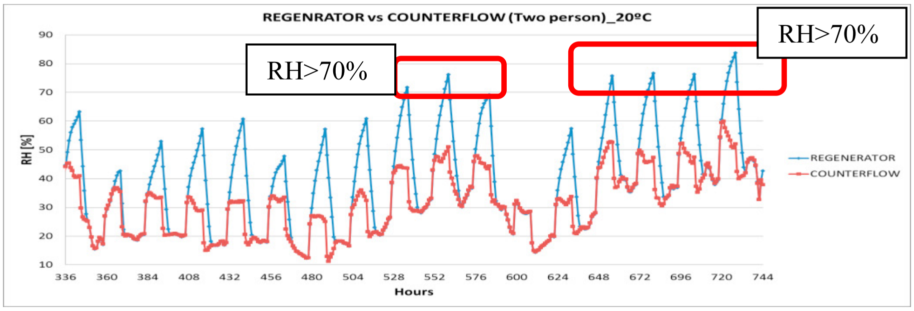

Fig. 3. Room relative humidity calculated for second half of January with 2-person load

Presented in Fig 2 and 3 results assume that all condensation in the regenerator evaporates back to the inlet air in the consecutive ventilation cycle; however, this is a critical assumption. In reality, only a fraction of the condensation could occur in the regenerator due to the fact that hot and humid exhaust air would pass through the regenerator very fast and not necessarily all vapors would condense. Another issue that could decrease indoor humidity levels is the fact that not all condensation in the regenerator might evaporate back to the inlet air. The reason for that might be the situation in which condensation would occur only in the coldest part of the regenerator closest to the outdoor condition. In such situation, inlet air would have very short contact with condensation and, therefore, not sufficient time to absorb the entire condensation. To illustrate the problem, Fig. 4 has different scenarios plotted assuming that condensation evaporating back to the inlet air in the next ventilation cycle varies between 100 and 50 %.

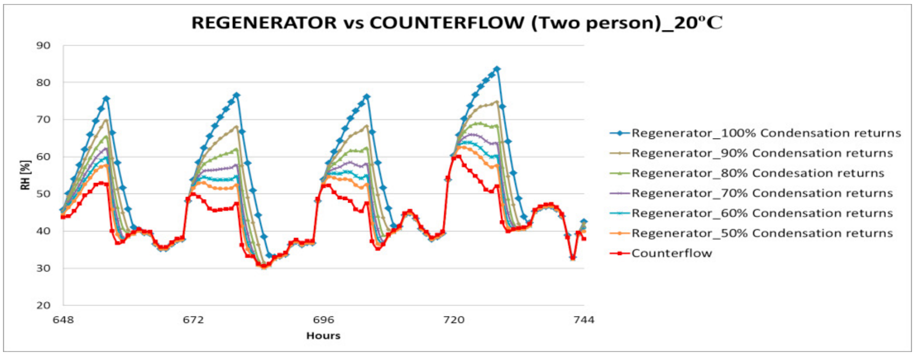

Fig. 4. Room relative humidity plotted for the last 4 days in January with 2-person load and different condensation turning back to the inlet air.

It should be noticed that relative humidity levels are significantly reduced if only a fraction of the condensation finds its way back to the room. Still, condensation that does not evaporate back to the room in the next ventilation cycle stays in the regenerator and must be drained out in order not to accumulate in larger quantities in the ventilation AHU.

4. Discussion

The presented calculations compare the performance of regenerator and the counter-flow heat recovery system in the standard size bedroom with typical moisture load, namely one or two persons. In the calculation it was taken into account that the activity of a sleeping person is decreased to 0.8 met and, therefore, moisture generation is also reduced to 0.4 kg H_2O/h person. The infiltration is assumed at 0.13 1/h and fulfills demand for building tighness according to [2]; however, this parameter could be arguable and set to higher value for older and less tight buildings.
For the chosen air flow at 25 m^3/h (7 l/s) corresponding to air flow recommended for 1 person in building class II in [3], it can be noticed that there is significant difference in performance of regenerator system with regards to relative humidity in the room if the room is ocupied by 1 and 2 persons. It should be stressed that for the scenario with 2 persons, the airflow was kept at 25 m^3/h which means that the air per person was decreased by 2. As an implication there is significantly more condensation in the regenerator, and relative humidity in the room might become significantly higher than for room ventilated with counter-flow exchanger. For a 20ºC room temperature there is the risk that the relative humidity might increase above 70% for some periods in the winter period. This risk would be minimized if the room temperature is kept somewhat higher and with that the regenerator temperature would not drop below dew point of outdoor air, for example, at 22ºC. To avoid a high relative humidity in rooms ventilated with a regenerator heat exchanger, it is recommended to keep minimum airflow at 7 l/s person. On the other hand, relative humidity in the room with counter-flow exchanger is dry in the winter period. It fluctuates between 10 and 50 % and for some periods between 10 and 30% what also can lead to discomfort.

5. Conclusions

- The paper has presented an hourly calculation method to determine the humidity in a room ventilated with DVS with regenerator heat exchanger.
- Humidity levels in the room have been compared to a standard ventilated room with counter-flow exchanger.
- In the calculations, it is assumed that condensation will form a thin layer on the regenerator surface and, therefore, might all evaporate back to the room in the next cycle. In such a case, the humidity level will build up in the room, and the system with regenerator will not be able to dehumidify the air in the room as efficiently as the system with counter-flow exchanger.
- Presented results are theoretical. Due to the complexity of the condensation phenomenon in the regenerator presented in this paper, results must be validated by the test measurements. Tests will be performed in the special test climate chamber.
- Assessment of humidity in the room shall always include infiltration. For European climate condition the higher the infiltration – especially in the winter – the lower the relative humidity in the room.
- The calculation does not included the sorption effect of building materials that would somewhat decrease low and high humidity peaks in reality.

Acknowledgements

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[2] Danish Building Regulations 2015
[3] EN 15251 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.