7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA
September 23 - 26, 2018

Healthy, Intelligent and Resilient
Buildings and Urban Environments
ibpc2018.org | #ibpc2018

Utilization of heat recovery ventilation: steady-state two-zone heat loss analysis and field studies

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ABSTRACT

In new houses in Europe the share of mechanical ventilation with heat recovery is increasing as a result of more severe energy performance requirements and of energy labelling for residential ventilation units. The methods used to assess the influence of heat recovery ventilation on the heating energy use in energy labelling and certification are typically based on single zone energy balance equations, although heating behaviour and set-points differ in different rooms of a dwelling. As a result of this the energy savings of heat recovery ventilation as assessed with single zone methods may be larger than when the spatial variations in dwellings are taken into account. This is related to the fact that the recovered heat supplied to the dwelling through the ventilation system is not 'useful' to reduce space heating and cooling demand at all time and in every room.

A two-zone steady-state heat loss analysis was conducted to investigate the relation between spatial variations in a dwelling and the utilization of heat recovery. One zone represents the rooms in a house which are regularly heated and are typically equipped with heat emitters and local controls. The other zone represents the rooms which are rarely heated or have no individual heat emitters or controls.

The results show the differences between a single zone and two-zone approach in terms of the effects of heat recovery ventilation on building heat loss, and define the main influencing parameters for the utilization of heat recovery in residential ventilation systems.

The analysis is supported by results of a field study where energy use in 114 low-energy houses was monitored. Half of the houses had mechanical ventilation systems with heat recovery, while the other half had demand-controlled mechanical extract ventilation. Apart from the differences in ventilation systems, the houses were largely identical.

KEYWORDS

Heat recovery ventilation, Building heat loss, Temperature zoning, Energy performance

INTRODUCTION

The European market for residential ventilation is highly driven by energy performance regulations. In new buildings the share of mechanical ventilation with heat recovery (MVHR) is increasing as a result of more severe energy performance requirements. For instance in Belgium the share of MVHR in new single family houses has increased in 10 years' time from 25% to almost 50% since the introduction of the energy performance regulation in 2006 (VEA, 2015). The energy labelling for residential ventilation units and the ecodesign requirements for ventilation units may further contribute to the wide-spread application of MVHR in new buildings (EC, 2014).

However, at the same time research reveals a performance gap between the rated energy performance of residential buildings and the actual energy use. The effect of energy saving measures is typically overrated compared to reality. Majcen et al. (2016) found that in 280 houses where mechanical exhaust ventilation was replaced by MVHR the actual reduction in gas use was less than a quarter than what was expected based on the EPC-rating. One possible cause of the discrepancy is a poor installation quality of the ventilation unit, resulting in shortcuts and leakage that may decrease dramatically the efficiency of heat recovery (Roulet et al. 2001). Another cause of the discrepancy is the simple model used in rating methods to calculate the ventilation heat loss, perhaps not sufficiently accurate to reflect the actual influence of the heat recovery system (HRS).

Indeed, the methods used to assess the influence of heat recovery ventilation on the energy use of buildings in energy labelling and certification are typically based on single zone steady-state energy balance equations, using the thermal efficiency or heat exchange effectiveness of the HRS as an input. The single zone approach assumes that all rooms are heated to the same set-point temperature and that the extract air temperature equals room temperature. Intermittency and multi-zoning is not considered although heating behaviour and set-points may differ in different rooms of a dwelling. In a typical lay-out of MVHR air is extracted from wet rooms with lower set-point temperatures than the main living areas and recovered heat is also supplied to unheated habitable rooms (eg bed rooms), unnecessarily increasing the indoor temperature and heat loss in the latter rooms. As a result of this the energy savings of heat recovery ventilation as assessed with single zone methods may be larger than when the spatial variations in dwellings are taken into account.

Faes et al. (2017) assessed the influence of MVHR on the space heating demand of a detached dwelling using dynamic simulations with a 10-zone-model and defined different ‘use factors’ to take temporal and spatial variations in temperature into account . Their results show that less than 50% of the heat recovered from the extraction air is actually supplied usefully to the rooms of the dwelling, in the sense that the recovered heat contributes to the reduction of yearly heating demand. Furthermore the relative influence of MVHR on the heating demand increases with higher thermal resistance and airtightness of the building envelope. A high performance building envelope causes the temperature throughout the dwelling to be more constant over time and uniform with respect to the different spaces. As a result the single zone assumption is valid and the thermal efficiency of the HRS better reflects the energy savings of MVHR. However, as Berge et al. (2016) observed in field studies in Norway, inhabitants of highly insulated dwellings with heat recovery tend to apply extensive window ventilation in bedrooms to compensate for the undesired oversupply of heat to these rooms. This leads to an increased space-heating demand, and again reduces the potential energy savings of MVHR, and the validity of the single zone assumption.

In this work, a two-zone steady-state heat loss analysis is conducted to investigate the relation between spatial variations in a dwelling and the utilization of heat recovery to reduce the building heat loss. A definition of the ‘useful’ efficiency of MVHR is proposed and compared to the thermal efficiency of the HRS. The results show the differences between a single zone and two-zone approach in terms of the effects of heat recovery ventilation on building heat loss, and define the main influencing parameters for the utilization of heat recovery in residential ventilation systems. The analysis is supported by results of a field study where energy use in 114 low-energy houses in a carbon neutral social housing district was monitored (Janssens et al. 2017). Half of the houses had mechanical ventilation systems with heat recovery, while the other half had demand-controlled mechanical extract ventilation. Apart from the differences in ventilation systems, the houses were largely identical.

METHODS

Heat loss analysis

In order to take spatial temperature variations within a dwelling into account different methodologies exist, ranging from correction factors introduced in a single zone model to a coupled multi-zone representation of a house (Delghust et al. 2015). Here a two-zone approach is chosen as a first order improvement of the single zone assumption. One zone represents the rooms in a house which are regularly heated and are typically equipped with heat emitters and local controls, such as living room and kitchen. The other zone represents the rooms which are rarely heated or have no individual heat emitters or controls, for instance bedrooms, bath rooms and hallway. Figure 1 shows the model parameters in a single-zone and two-zone representation of a dwelling with MVHR.

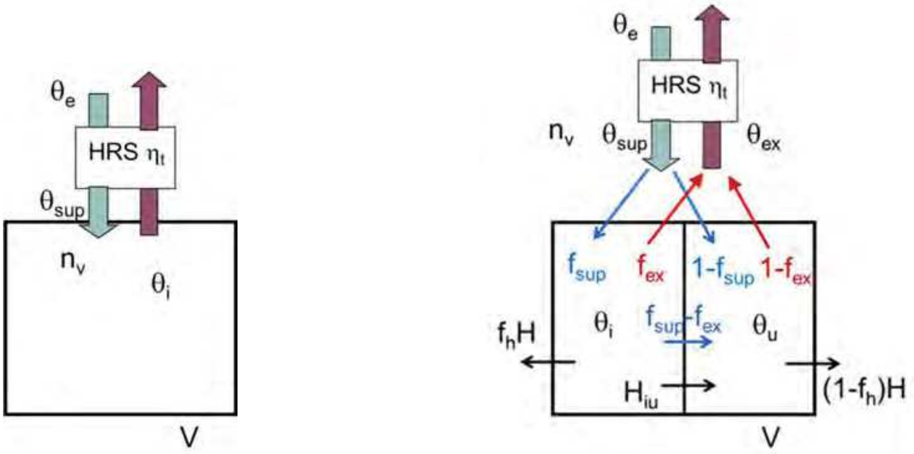

Figure 1. Single-zone model (left) and two-zone model (right) of a dwelling with MVHR, with indication of model parameters: η_t, thermal efficiency of HRS (-); V, building volume (m³); n_v, ventilation air change rate (h^{-1}); θ_e, exterior temperature (°C); θ_i, set-point temperature in heated zone (°C); θ_{sup}, supply air temperature (°C); θ_{ex}, extraction air temperature (°C); θ_u, balance temperature in unheated zone (°C); H, heat loss coefficient of building envelope (W/K); H_{iu}, heat loss coefficient of partition walls between heated and unheated zone (W/K); f_h, fraction of building envelope heat loss related to heated zone (-); f_{sup}, fraction of supply air supplied to heated zone (-); f_{ex}, fraction of extraction air extracted from heated zone (-).

The overall steady-state heat loss Φ_L (W) of the heated zone is defined by Eq. 1 and Eq. 2 in the single-zone and two-zone model, respectively:

$$\Phi_{L,1z} = [H + 0.34 n_v V(1-\eta_t)](\theta_i - \theta_e) \tag{1}$$

$$\Phi_{L,2z} = f_h H(\theta_i - \theta_e) + H_{iu}(\theta_i - \theta_u) + 0.34 f_{sup} n_v V(\theta_i - \theta_{sup}) \tag{2}$$

The heat loss equation of the two-zone model may be solved using the heat balance equation of the unheated zone to find θ_u (Eq. 3) and the heat transfer and mixing equation of the supply and extraction air to find θ_{sup} (Eq. 4).

$$\begin{aligned}\left[H_{iu} + 0.34(f_{sup} - f_{ex}) n_v V\right](\theta_i - \theta_u) \\ = (1 - f_h) H(\theta_u - \theta_e) + 0.34(1 - f_{sup}) n_v V(\theta_u - \theta_{sup})\end{aligned} \tag{3}$$

$$\theta_{sup} = (1-\eta_t)\theta_e + \eta_t[f_{ex}\theta_i + (1 - f_{ex})\theta_u] \tag{4}$$

Expression of results

The heat loss calculation is applied for different values of the heat loss coefficient H of the building envelope, using typical values for the other model parameters (Laverge et al. 2013): $V = 500\ m^3$, $n_v = 0.5\ h^{-1}$, $H_{iu} = 200\ W/K$, $f_h = 0.5$, $f_{sup} = 0.45$, $f_{ex} = 0.30$ *and* $\eta_t = 0.80$.

The overall heat loss of the heated zone of the dwelling with MHRV is compared to the heat loss of the dwelling with a ventilation system without HRS, eg mechanical exhaust ventilation (MEV) or mechanical ventilation with $\eta_t = 0$. The difference between both defines to what extent the overall heat loss is reduced by the application of MVHR. The ratio between this difference and the extra heat loss incurred by adding ventilation defines the specific heat loss reduction or 'useful' efficiency of the HRS in Eq. 5 (called 'use factor' by Faes et al. 2017) :

$$\eta' = \frac{\Phi_{L,MEV} - \Phi_{L,MVHR}}{0.34 n_v V(\theta_i - \theta_e)} \tag{5}$$

When applying the single-zone model, the useful efficiency η' is equal to the temperature efficiency η_t of the HRS, independent of other parameters.

RESULTS

Calculated useful efficiency

Figure 2 shows the results of the two-zone heat loss analysis for the parameter values given in the previous paragraph. The dimensionless temperature in the unheated zone and the useful efficiency are depicted as a function of the volumetric heat loss coefficient of the building envelope *H/V*. The right hand side of the x-axis corresponds to poorly insulated envelopes, the left hand side to highly insulated envelopes. The temperature in the unheated zone decreases with higher values of heat loss coefficient. In the dwelling with MVHR the unheated zone is slightly warmer than with MEV since air preheated by the HRS is supplied to the unheated zone. Since the supply air temperature of MVHR depends on the temperature of the extraction air and a large share of the extraction is taken from the unheated zone, the supply air temperature also decreases with higher values of heat loss coefficient, thus diminishing the heat loss reduction provided by MVHR. This effect is reflected in the calculated useful efficiency, which remains substantially lower than the value of the thermal efficiency of the HRS (equal to the useful efficiency in the single-zone approach). With better insulation of the building envelope and lower ventilation rates, the useful efficiency predicted by the two-zone model increases towards the result of the single-zone model.

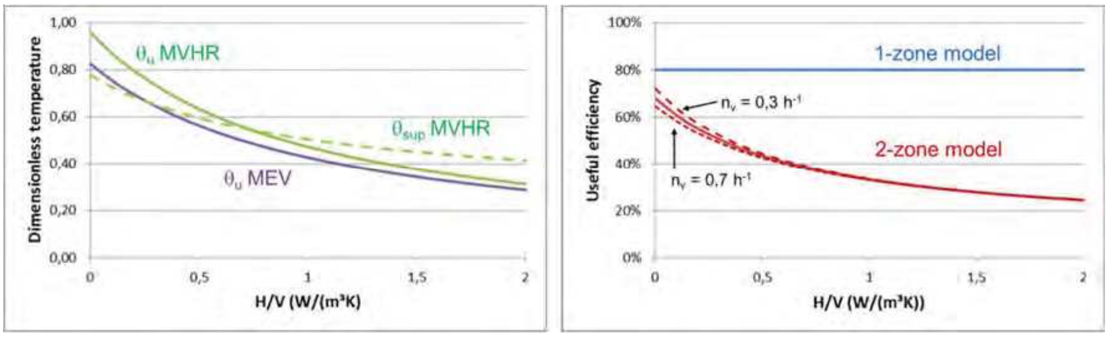

Figure 2: Results of two-zone heat loss analysis: dimensionless temperature in unheated zone with MEV and MVHR and supply air temperature with MVHR (left) and useful efficiency η' following from two-zone model compared to single zone model (right).

Field study

The heat loss analysis shows that the energy performance of MVHR largely depends on modelling assumptions. Still, both the 1-zone and 2-zone model remain simplifications; in reality the spatial variations in temperature in dwellings are in between both modelling extremes. To put the results of the theoretical analysis into perspective monitoring results of a field study are now discussed, where the total metered heat use (space heating and sanitary hot water) in the dwellings of a carbon neutral housing district was compared to the heat use rated in the energy performance certificates. In Belgium the energy performance of new and renovated buildings needs to be assessed at the moment of completion of the works by an EPB-assessor, who collects the as-built information, creates the input in the EPB-software, and evaluates whether the building meets the requirements. Half of the houses had MVHR with a rotary HRS (η_t = *80%*), while the other half had demand-controlled MEV. The volumetric heat loss coefficient of the building envelope was about 0.15 W/(m³K). In total 90 houses (41 MVHR, 49 MEV) had complete metering data to perform the comparison. More information about the district and the monitoring method is given by Janssens et al. (2017).

As Figure 3 shows, the rated heat use in houses with MEV was significantly higher than that in houses with MVHR, on average 32%. However, this is not reflected in the results of the monitoring where the metered heat use shows no significant difference between both types of houses. Apart from the ventilation system the houses were largely identical. Also the user behaviour in both groups of houses was similar according to the monitored living room temperatures, with average values in winter months 23.0±1.5°C for MEV and 22.7±1.5°C for MVHR. Temperatures in bedrooms were on average 3 to 4°C lower in both types of houses. Therefore differences in heating behaviour are no explanation for the deviation between rated and metered performance of the houses with MVHR.

An analysis based on the EPB input-files of the rated houses shows that the heat use in the houses with MVHR strongly depends on the input value of the thermal efficiency of the HRS (Figure 3, right). So the reduced useful efficiency of MVHR as a result of temperature differences between rooms may partly explain the underperformance of MVHR in terms of metered heat use. Furthermore large differences were measured between day zone temperatures and extract air temperatures in some houses, possibly related to window opening in wet rooms. This still needs to be investigated in more detail.

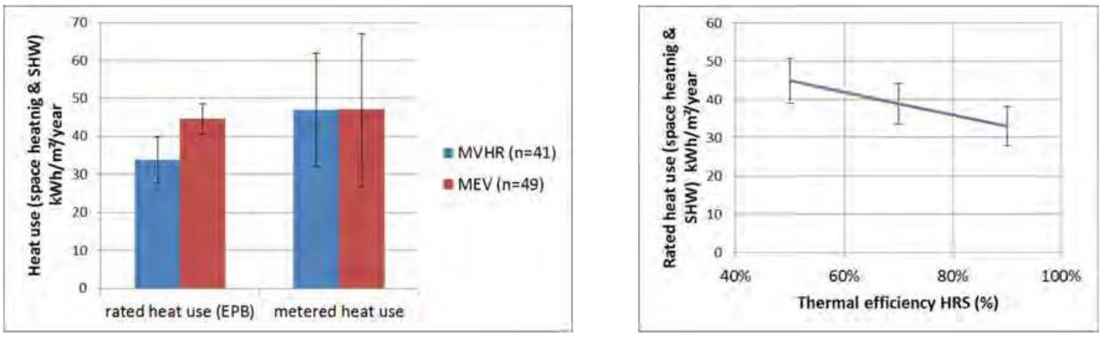

Figure 3: Comparison between the rated and metered (1/5/2015-30/4/2016) heat use of low-energy dwellings with MVHR and MEV (left) and relation between rated heat use of houses with MVHR and thermal efficiency of HRS, with specified thermal efficiency of 80% (right).

CONCLUSIONS

A two-zone steady-state heat loss analysis was conducted to investigate the relation between spatial variations in a dwelling and the utilization of heat recovery in mechanical ventilation. The results show that the building heat loss reduction of MVHR assessed by single zone methods typically used in energy labelling and certification is optimistic compared to the assessment of a two-zone model. When temperature differences between heated and unheated rooms are taken into account, the building heat loss reduction of MVHR is influenced not only by the thermal efficiency of the HRS but also by building envelope heat loss, flow rates and lay-out of the ventilation system, and size of day and night zone. Field studies show evidence that the positive influence of MVHR on heating energy use as predicted by single zone rating methods, is not confirmed by the metered heat use. A definition of the 'useful' efficiency of MVHR is proposed as a metric to take heat recovery ventilation into account in a more correct way in energy performance rating methods. With better insulation of the building envelope and lower ventilation rates, the useful efficiency predicted by the two-zone model increases towards the result of the single-zone model.

ACKNOWLEDGEMENT

This work was supported by the EU Concerto initiative, 'Sustainable Zero Carbon ECO-Town Developments Improving Quality of Life across EU' (ECO-Life) (TREN/FP7EN/239497/"ECO-Life"), http://www.ecolife-project.eu/index.html, project leader COWI, and by the Fund for Scientific Research (FWO) in the frame of the strategic basic research (SBO) project "NEPBC: Next generation building energy assessment methods towards a carbon neutral building stock" (S009617N). The support is gratefully acknowledged.

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