Efficiency of heat recovery ventilation in real conditions: feedback from several measurement campaigns

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ABSTRACT

Heat recovery ventilation (HRV) is one of the usual techniques (next to demand controlled) to reduce the energy impact of ventilation in buildings. For a given air change rate, the energy savings of HRV are in the first place dependent of the heat-exchanger efficiency, usually measured in standardized laboratory conditions. However, many other factors can have an impact on the overall system performance in practice. Through three different projects in the last years, BBRI had the opportunity to monitor about 15 systems during several months, allowing to (try to) evaluate their performance in real operation.

Before going into the details of the measurement campaigns, this paper gives a short overview of the various factor that can negatively affect the actual energy recovery compared to what could be expected from the heat-exchanger efficiency only. This overview will help to interpret and explain the monitoring results.

What concerns the monitoring campaigns, the temperature in the 4 flows of the heat exchangers were measured with a few minutes time step during several months. The frequency and the duration of the measurement allowed to compute the supply and exhaust efficiencies and derive statistics (mean efficiency, …), but also to observe more localized events like the triggering of frost-protection systems. In the two first campaigns, these temperatures were measured directly within the ventilation groups at the vicinity of the heat exchanger so that the measurements were not impacted by the heat released by the fans. For the last measurement campaign, the temperatures were measured in the ducts just before and after the ventilation unit. The outcomes of this measurement campaign are twofold:

- For most installations, the average efficiencies of the ventilation units (as computed in the Belgian EP calculation) are between 70% and 90%. These are quite in line with the declared product values (as published on www.epbd.be).
- Some of the results in the first two campaigns showed that a non-negligible temperature heterogeneity exists in some of the fluxes leading to biased evaluation of the efficiency. Furthermore, the monitored data of the third campaign showed less noise of unexplainable variations than in the first two campaigns. Even if the sample was quite reduced for this last campaign (5 installations), the trend seems quite clear and we would thus recommend this measurement method for future measurement campaigns.

KEYWORDS

Heat Recovery Ventilation, Efficiency, Field measurements

1 INTRODUCTION

Heat Recovery Ventilation (HRV) is one of the common techniques to reduce the energy footprint of ventilation in buildings in Belgium and more generally in northern Europe. This footprint becomes more and more important (in relative terms) as the requirements on building insulation become stronger with the evolution of the various building energy performance regulations.

The heat quantity that can be recovered through a HRV unit depends in the first place of the heat-exchanger efficiency, usually measured in lab conditions following appropriate standards. On-site operation is however different from idealized lab measurement, and one can expect a performance gap between lab and on-site measurements. A lot of factors can negatively impact the real heat recovery such as flow unbalance, leaks, insulation defect, fouling, etc. (Rouleta C. , 2001), (Rouleta C. A., 2001-2). Some field experiments at the building scale also show that the energy savings due to HRV seem lower than predicted by the applicable EPB calculation methods (Janssens, 2017).

In this context of questioning over real HRV energy efficiency, we had the opportunity to perform measurements on about 15 HRV units operating on-site in the frame of various research projects. Our target was first to verify if the efficiency claimed by the manufacturers were reached or approached in practice, and second to have an overview on how these systems were operating in practice: are their efficiencies constant? ; do the frost-protection correctly trigger ? ; is there any sign of malfunctioning ? ; etc.

2 HRV EFFICIENCY

2.1 Effectiveness, efficiency and temperature ratios

Strictly speaking, the effectiveness of a heat exchanger (ε) is the ratio of the actual transferred heat over the theoretical transferred heat if the heat-exchanger was perfect (counter-current and with infinite heat-exchange area). This maximum transferrable heat is determined by the side with the lower thermal capacity $\left(q_m C_p\right)_{min}$ (with q_m the mass flow [kg/s] and C_p the specific heat of the circulating fluid). If the fluid is the same on both sides of the heat exchanger, the lower mass flow determines the maximum heat transfer.

Applied to heat recovery ventilation, one can write:

$$\varepsilon = \frac{q_{m,eta}(T_{eta}-T_{eha})}{\min(q_{m,eta},q_{m,sup})(T_{eta}-T_{oda})} = \frac{q_{m,sup}(T_{sup}-T_{oda})}{\min(q_{m,eta},q_{m,sup})(T_{eta}-T_{oda})}$$

with q_m the mass flow rates and T the temperatures of the flows, with the following suffixes (illustrated in Figure 1).

- eta : ‘extracted air’
- eha : ‘exhausted air’
- sup : ‘supply air’
- oda : ‘outdoor air’

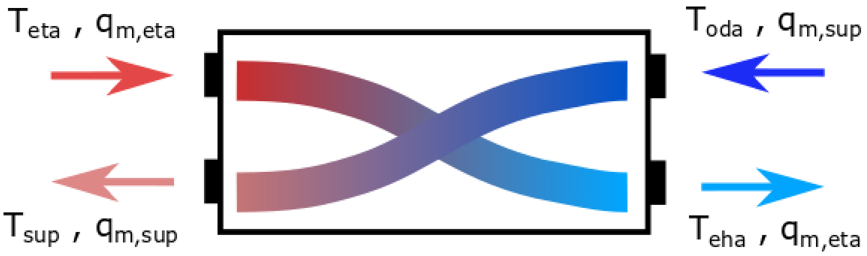

Figure 1 Flow and temperatures at the bounds of a heat exchanger or a HRV unit

In the context of (heat recovery) ventilation, the term "efficiency" is generally used instead of effectiveness; the term of "ventilation effectiveness" being used to quantify the quality of the air renewal. Further in this paper, we'll use the term "efficiency" (written η) to refer to the fraction of the heat that is recovered.

If the flows are perfectly balanced, the efficiency simplifies a temperature ratio that can be computed on both sides (supply or exhaust) of the heat exchanger.

$$\eta_{sup} = \frac{T_{eta} - T_{eha}}{T_{eta} - T_{oda}} = \eta_{eha} = \frac{T_{sup} - T_{oda}}{T_{eta} - T_{oda}} = \eta$$

Theoretically, η_{sup} and η_{eha} are perfectly equal, but generally not in practice for several reasons due to the ventilation unit itself or due to global ventilation system (flow balance, heat released by the fans, etc.).

In the field of ventilation, efficiency is often calculated using temperatures only, not considering these perturbating effects. Further in this paper, η_{sup} and η_{eha} will be named temperature ratios to make a clear distinction with the real efficiency.

2.2 Factors influencing HRV Energy efficiency at system or building scale

The heat exchanger efficiency is the most influencing factor on the energy that is recovered. However, a lot of other factors can have a significant impact. The global energy efficiency at system or building scale is in practice different from the lab-measured efficiency of the heat-exchanger or the unit. The most influencing factors are shortly described here below.

Flow imbalance

The flow imbalance between supply and exhaust is always negative regarding the energy efficiency at building or system scale. The energy that is recovered in the heat exchanger is limited by the smallest flow rate.

The flow imbalance is then compensated by extra in- or exfiltrations through the building envelope (whose energy loss is not compensated by the heat recovery).

- If the supply is higher that the exhaust (overpressure), more hot air leaves the building by exfiltration
- If the exhaust is higher than supply (underpressure), more cold air enters the building by infiltration

In both cases, this leads to an extra energy loss. Roughly, if the highest flow rate is considered as reference, the recovered energy decreases linearly with the imbalance. This is illustrated by a theoretical calculation using a e-NTU model in Figure 2. The temperature of the low flow side increases and tends to 1 as the flows become unbalanced. This determines the maximum transferable heat quantity as described in the formal definition of “effectiveness”. However, if considering that the flows are in any case balanced at the building scale (by extra in- or exfiltrations), the recovered energy decreases with imbalance. The real ‘energy efficiency’ is the temperature ratio of the high flow side (that decreases with imbalance).

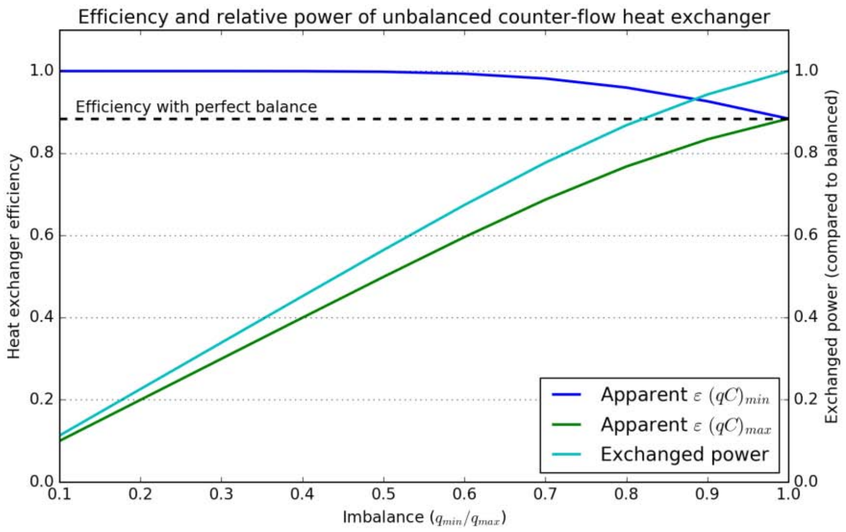

Figure 2 Temperature ratios (left axis) and exchanged energy (right axis) for an imbalances heat-exchanger.

Leaks

Duct leaks or leaks within the ventilation unit either lead to imbalance at the heat exchanger or lead to extra in- or exfiltrations. In both cases, this is an energy loss.

Absence or lack of duct insulation

There are globally two temperature levels: hot side (supply and extract) and cold side (exhaust and outdoor). Part of the recoverable energy is lost if there are:

- Non isolated cold ducts within heated spaces
- Non isolated hot ducts in unheated spaces

For a typical residential installation (250 m³/h, main duct of 200 mm diameter), we computed that 3 to 4 m non isolated ducts can reduce the heat recovery potential of 10%.

Thermal insulation of the unit

The energy balance and efficiency calculations suppose that the system is closed and that there is no heat loss towards outside, which is naturally not perfectly the case in practice.

Building dynamics and temperature difference between zones

Some research works (Janssens, 2017) (Faes, 2016) showed through theoretical models and thermal dynamic simulations that all the energy recovered by a HRV unit does not necessarily lead to a reduction of the heating demand.

Without entering into the details, these demonstrations rely on the fact that all the rooms are not necessarily heated at the same temperature and that the heat recovery is not always synchronous with the presence of occupants and the heating needs (in the latter case, energy recovery 'looses' part of its interest).

2.3 HRV in Belgian EP-regulations

To be used in the EP calculations in Belgium, the heat-exchangers or ventilation units must be tested following a specific test method (Méthode PER - Annexe G - Détermination du rendement themrique d'un récupérateur de chaleur), mostly following NBN EN 308 standard.
During the test, even in lab conditions, there are several factors influencing the apparent efficiency:

- The perfect flow balance (see §2.2) is very difficult to reach
- The heat released by the fans changes the temperatures levels
- Leakages or transmission heat losses of the units

It has been shown (Caillou, 2009) (Caillou, 2012) that most of these issues tend to increase the supply efficiency and to decrease the exhaust efficiency. That's why a specific test method and calculation procedure has been developed in the frame of the Belgian energy performance regulations. One of the key points of the method is that the final efficiency from the test is the average of apparent η_{sup} and η_{eha}.

This way of doing was demonstrated as robust to the various uncertainties listed above (Caillou, 2009), (Caillou, 2012) and representative of the HX or HRV unit true efficiency in balanced conditions. Further in this document, the mean efficiency (mean of 'supply' and 'exhaust') will be named η_{epbd} in reference to Belgian EP-regulation.

To illustrate this rationale, Figure 3 re-uses the example of imbalanced flow with a theoretical model. Until an unbalance of 20% (flow rate ratio of 0.8) , making an average of the supply and exhaust efficiency remains very close to the 'balanced' efficiency of the heat-exchanger. This rationale can be applied to other perturbations that have a symmetric effect like the fan heat for example.

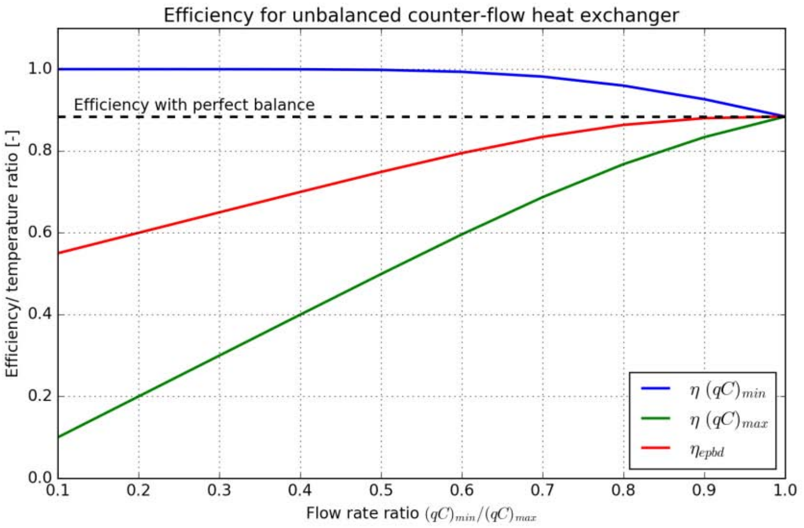

Figure 3 Theoretical example of apparent efficiency for imbalanced heat-exchanger. The 'epbd' efficiency remains close to the 'balanced efficiency' up to a flow rate ratio of 0.8 (20% imbalance).

Note that the test procedure has for target to determine the efficiency of the ventilation units in perfectly balanced conditions. The impact of possible imbalance at the system scale is taken into account in a later stage in the EP calculation method, with correction factors that depends on the whole ventilation system.

3 MEASUREMENT CAMPAIGNS AND RESULTS

In the frame of various research projects, 16 different HRV units have been monitored in situ for several months by measuring the temperatures at the four bounds of the units. For each unit, these four temperatures allow to compute both supply and exhaust apparent efficiency as defined in §2.1.

The initial objectives of these successive campaigns were on one side to verify if the heat-exchanger efficiency were equal or close to the lab-measured efficiency, and on the other side to see if there were any malfunctioning, and if relevant, try to identify the most common ones. These campaigns were also an opportunity to learn about the measurement methodology itself.

3.1 First campaign

The first measurement campaign occurred in the frame of the OPTIVENT project (funded by VLAIO - Flanders Innovation and Entrepreneurship Agency). Nine operating installations were monitored during one to three months.

In this campaign, the data loggers (measuring temperature and humidity) were placed directly inside the unit at the bounds of the heat exchanger, downstream of the fans so that the calculated temperature ratios are representative of the heat exchanger only and not perturbated by the fans heat. The used data loggers had been calibrated (for temperature) in lab conditions before being installed on site.

Figure 4: Example of temperature logger placement for the first measurement campaign. The heat-exchanger has been removed to place the sensors

We have also performed flow measurement for some of the units. This was a single measurement performed at nominal operation point at the beginning of the project. This allow to evaluate the flow imbalance, that can help explaining some of the results.

We consider this evaluation of (im)balance as qualitative since:

- The flows have been measured by summing the measured flow at the terminal devices. They may not be exactly equal to the flow through the heat exchanger if the ductwork airtightness is not perfect
- The balance of the installation may have changed during the monitoring period (fouling, cleaning or replacement of the filters during the monitoring period)

For this campaign, we choose to present more in detail the measurement results on 3 out of the 9 monitored installations. These results are representative of 3 types of results we observed in the campaign.

Normal situation

Monitoring results for the first site are presented in Figure 5. Results were available with a 10 minutes frequency and have been averaged over 1 hour. Both the supply and exhaust temperature ratios show 'high frequency' oscillations, but their average value is very close to 70%. By definition, the 'epbd' efficiency (average of the two ratios) is also about 70%.

The frequency of the oscillations is about a few hours. A closer analysis showed that these variations occur with indoor or outdoor temperature variations, but with no systematic correlations. Overall, the behavior of this unit seems quite normal.

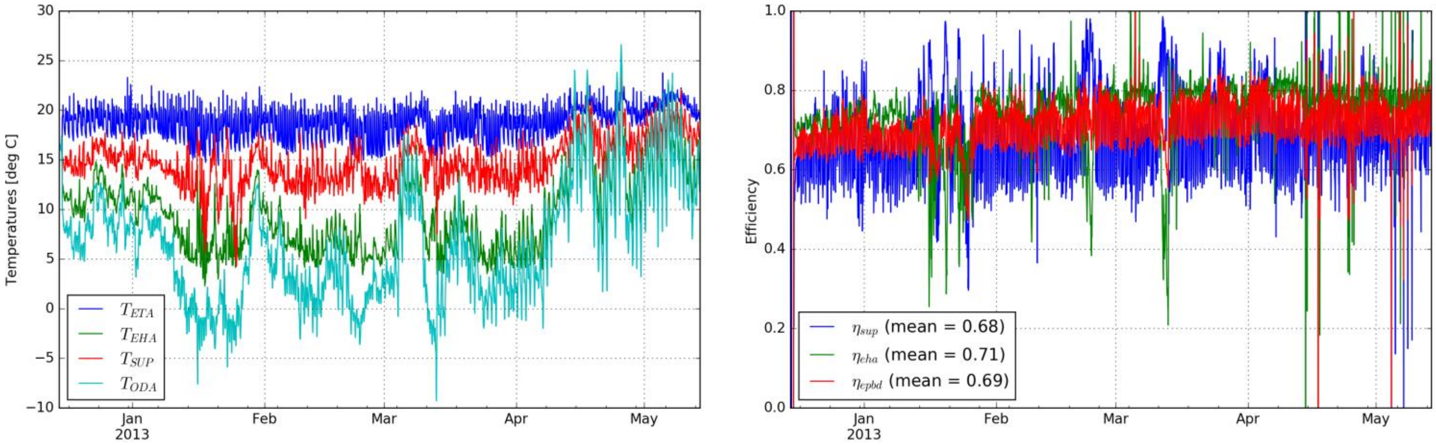

Figure 5 Measured temperatures and apparent efficiency for site 1

Almost normal situation

Results for a second installation are given in Figure 6. For this second case, one can first observe a systematic difference between the two temperature ratios. The 'exhaust' ratio is systematically higher than the 'supply' one, and this difference increases with time. Some possible explanations for this difference have been listed in §2.1 (flow unbalance, location of the sensor close to a thermal bridge, etc), but we do not have enough information to accurately identify the issue. One will also note that the difference between ratios occurs at higher external temperatures, which is less impacting in terms of yearly energy recovery.

It is interesting to note that the ‘epbd’ efficiency remains more or less constant (between 70% and 80%) during the whole test period.

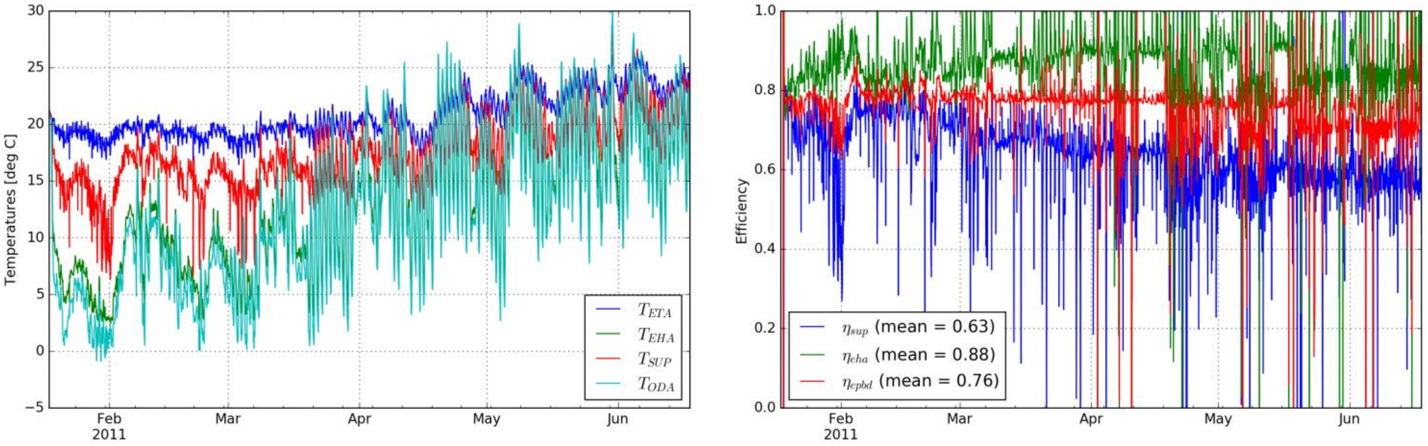

Figure 6 Measured temperatures and temperature ratios for site 2

Abnormal situation

Results for the third analyzed case are given in Figure 7. One observes a very high exhaust temperature (EHA), close to the supply one. When computing the temperature ratios, this leads to a very low value on the exhaust side while the supply value seems quite normal around 0.8.

For this installation, we know from air terminal devices measurements that the extracted flow was about 30% higher than the supply flow. This can explain a part of the difference, but not in this order of magnitude. The location of the sensors in the wake of the heat exchanger could also have an impact (see §3.3).

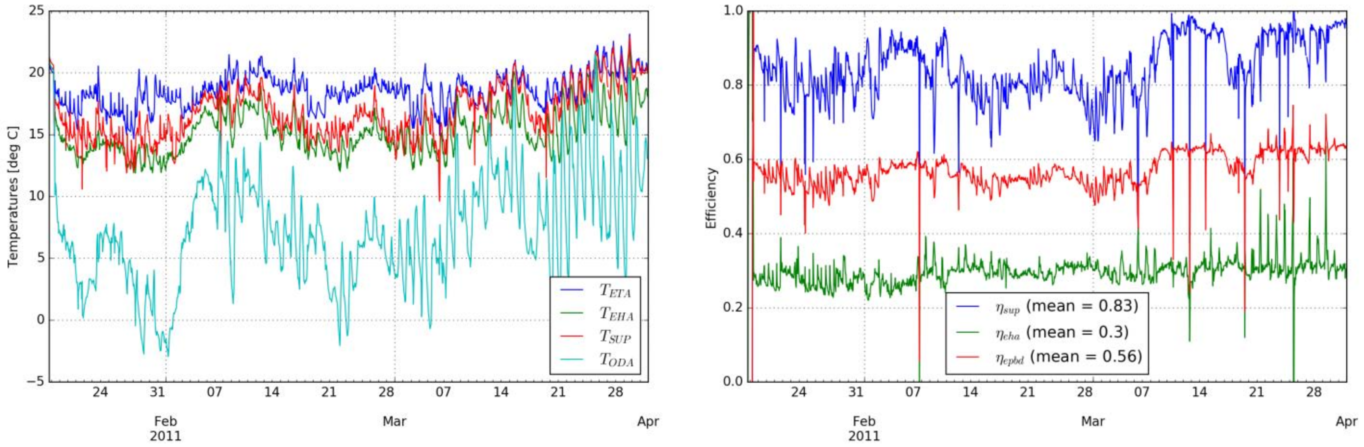

Figure 7 Measured temperatures and apparent efficiency for site 3

Overview of other results

Only 3 out of 9 cases have been presented here. They were selected to show an overview of all kind of encountered results.

If looking at the 9 installations globally, there were only 2 “abnormal” cases on the whole set. The 7 other cases can be considered as “normal” or “almost normal”. For these, the average ‘epbd’ efficiency was between 0.7 and 0.8. Out of these 7, the difference between the two temperature ratios was higher than 0.2 for only one case (but with an average > 0.7). This could possibly be explained by a flow imbalance, as illustrated in Figure 3 (but it could not be verified).

3.2 Second campaign

The second campaign was performed with similar conditions and material as the first one. This time, only 4 installations were monitored, among which 2 were already part of the first campaign. For 3 of the measurements, the calculated ‘epbd’ efficiency was once again between 0.7 and 0.9 and are very comparable to the results of the first campaign.

The last installation that was monitored is the same as Case 3 of the 1st campaign, i.e. the “abnormal case”. For this second period of monitoring, the temperature loggers were doubled, i.e. two sensors were placed at each bound of the heat-exchanger. This test was done to test if there was some temperature heterogeneity in the flow close to the heat exchanger. The position of the dataloggers for this experiment are visible on the different pictures in Figure 8.

Figure 8 Positioning of the data loggers for the experiment with doubled sensors

Monitoring results are given in Figure 9. The left plot shows the temperature difference between the two sensors of each position (SUP, ETA, EHA, ODA). The right plot shows the temperature ratios and epbd efficiency. One observes significant difference between the ratios, that are due to temperature differences between sensors at the SUP and mostly at the EHA position.

The average difference on the SUP side is 0.15°C on the monitoring period, and 2.3°C on the EHA side. Sensors have an accuracy of 0.2°C and are regularly calibrated, so such large measurement error is excluded.

The only possible explanation is that there are effectively temperature differences in the flow rate in the unit, either due to very nonhomogeneous flow out of the heat exchanger, either due to local effect of the unit insulation. In the EHA flow rate, there can also be an effect of the condensation of water during some periods.

It is particularly interesting to observe that the temperature differences are very low in the flow position upstream of the heat exchanger (ETA and ODA) and quite higher downstream of the heat exchanger and close to the fan (EHA and SUP). One possible explanation could be that the proximity of the fan has higher impact on the non-homogeneity of the flows after the heat exchanger, while the flow before the heat exchanger would be more homogeneous.

Note that the results of the worst series (suffix ‘2’) are comparable with the results of the first campaign on this installation.

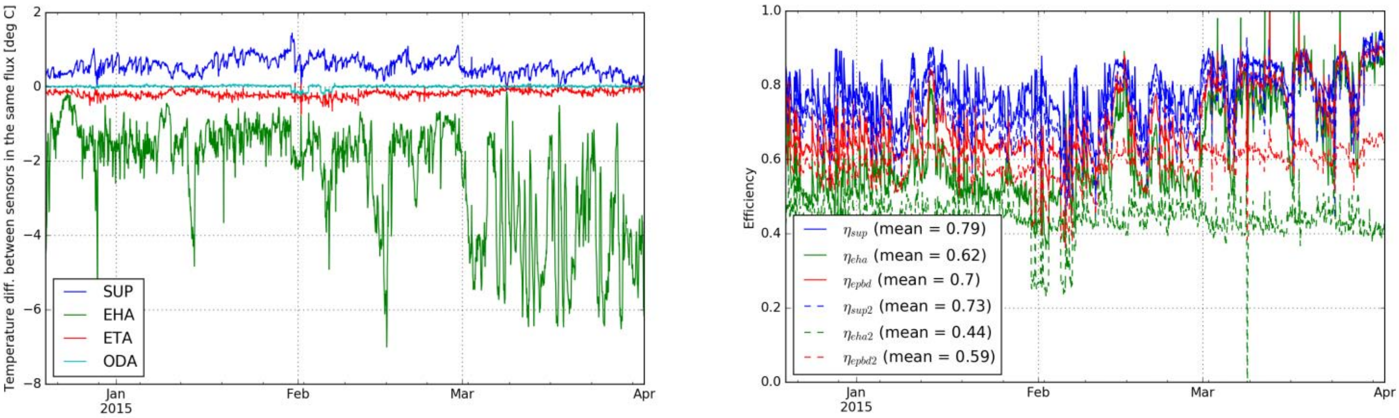

Figure 9 Experiments with doubled sensors: temperature difference between sensors at the same position and temperature ratios

3.3 Third campaign

In the frame of a third project (MEASURE – Funded by the Walloon Region), we had the opportunity to measure the heat recovery efficiency of 5 other HRV units on-site. Given the feedback from first campaigns, the sensors have been placed in the ducts just upwards and downwards of the ventilation unit, and not in the unit itself. These measurement conditions are similar to those used for laboratory measurement of ventilation unit according NBN EN 308 in the context of EPB regulation.

Flow measurement were performed by measuring the air flow rates at the supply and extract air terminal devices, but not necessarily at the same period as the temperature were measured. Temperature ratios were computed without the correction for fan power. This is different from what is done in the context of EPB regulation (where the efficiency is corrected for fan heat). However, the calculated average efficiency is less affected because the average neutralizes this effect symmetrically for the supply and exhaust efficiencies.

Table 1 summarizes the average efficiencies for the various dwellings on the measurement period. One observes for all the dwellings that the η_{sup} ratios higher than η_{eha}. This may be partially due to fan heat, as explained here above. For dwelling 4 for which the η_{sup} is 1, one can probably suspect strong flow unbalance as it was illustrated by a theoretical model in Figure 3.

The average values are all close to 80% in average, which is reasonably close to the values from the lab-tests for the concerned models (in the sample of 5 units, there were 2 different models with a declared value of 0.84 for both).

Figure 10 and Figure 11 illustrate the temperature and temperature ratios measurements for dwelling 1 and dwelling 3 of this campaign. Similar curves were obtained for all dwellings of this campaign. Compared to results of the two first campaigns, the curves are less noisy and seem more stable in time. Part of this difference could maybe be explained by a better quality or commissioning of these 5 units, but we have no objective reason to suppose these are better than the previous ones. More probably, we believe that the new measurement method (in the ducts upwards and downwards the ventilation unit) provides more representative results than the previous one (sensors upwards and downwards the heat-exchanger, within the ventilation unit) due to a more homogeneous temperature in the ducts than at the vicinity of the heat-exchanger.

Table 1 Average temperature ratios (sup,eha) and epbd efficiency on the whole measurement period for the 3rd measurement campaign

Dwelling	**1**	**2**	**3**	**4**	**5**
$\eta_{sup,av}$	0.89	0.85	0.86	1.01	0.83
$\eta_{eha,av}$	0.8	0.76	0.69	0.7	0.76
$\eta_{epbd,av}$	0.85	0.8	0.78	0.85	0.8

Next to the average values and the general shape of the curves, one could observe some punctual phenomena like the triggering of the frost protection or the by-bass. An example of it is visible in Figure 10. At two different moments (begin and mid-January) the ODA temperature drops below 0°C. At these periods, one can clearly see that the asymmetry between supply and exhaust ratios increases. This is probably explained by reduction of the supply flow, in order to prevent the exhaust (EHA) temperature to drop. One observes that this temperature never decreases below 5°C even though the outdoor temperature continues decreasing. We observed this kind of punctual phenomena several times in the different monitoring results, but it is not the main focus of the present paper. It will not be further developed here.

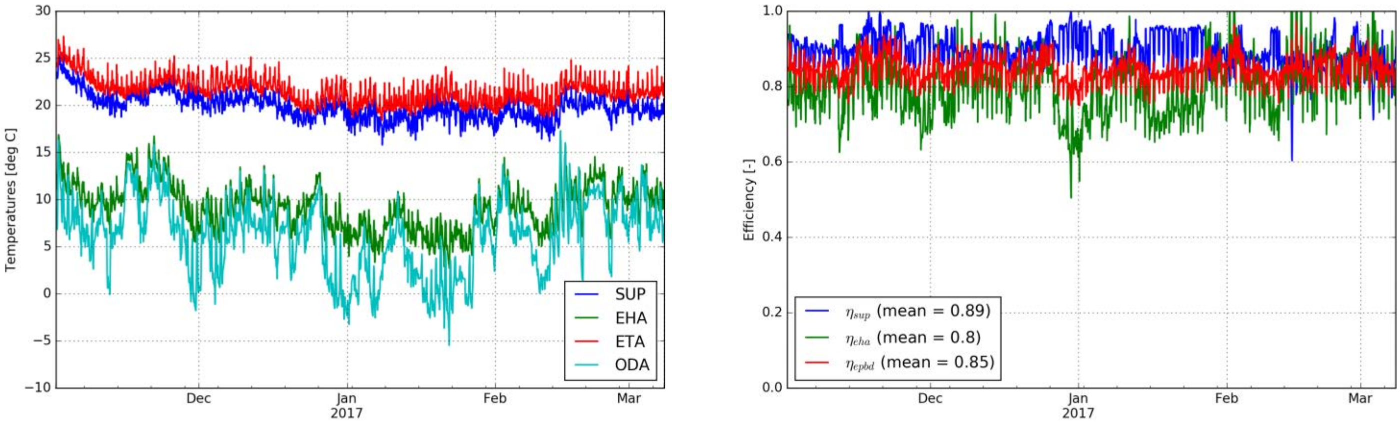

Figure 10 Measurement results for dwelling 1 of the 3rd campaign (from November 2017 to March 2017)

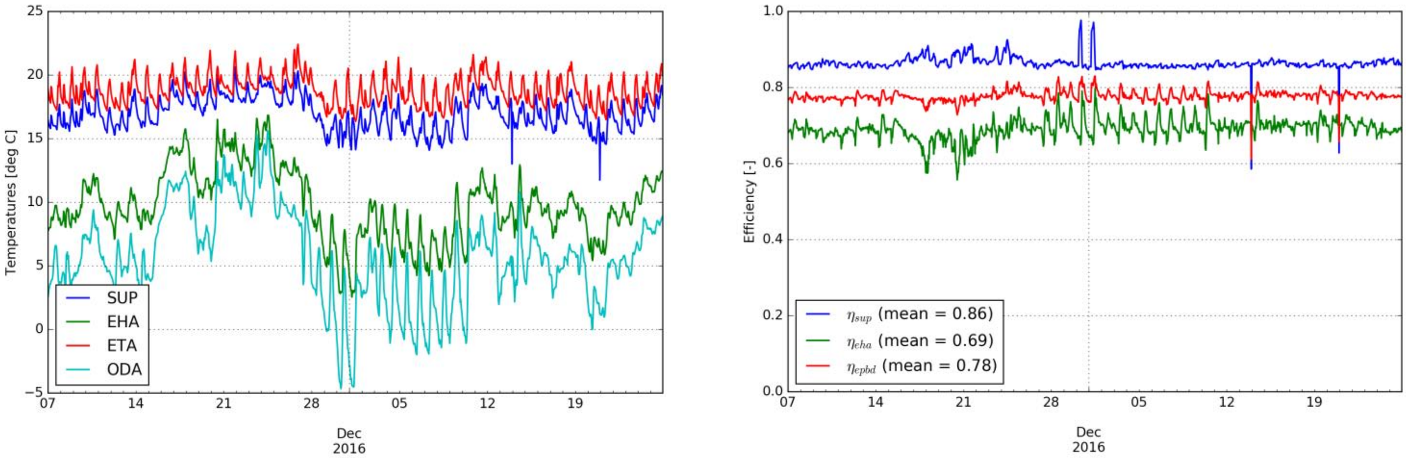

Figure 11 Measurement results for dwelling 3 of the 3rd campaign (from 7 November to 26 December 2016)

4 CONCLUSIONS

The main objective of this paper was to verify if the efficiency of HRV units operating on-site was consistent with the values obtained in lab-measurements.

We also recalled that heat-exchanger or ventilation unit efficiency is not the global energy efficiency and gave a short overview of the main issues that can negatively impact it. These reminders also highlighted that it is not that easy to decorrelate both, since some phenomena at the system scale (e.g. flow imbalance) can impact the temperature ratios measurements at the unit scale.

Regarding the on-site measurement itself, we showed that if computed the same way as in the lab-conditions (average of the supply and exhaust temperature ratios, following the Belgian EPB approach), the efficiency of the tested units was between 70 and 85% for most of them. Over the 16 different tested units, two of them showed problematic behaviour.

One experiment performed with doubled sensors showed that measurements directly within the unit (upwards and downwards the heat-exchanger) were highly sensitive to the sensor location. This is probably explained by temperature heterogeneity of the flow at the heat-exchanger outlet, even if there are other possible explanations (local condensation, thermal bridge). The last campaign with measurement in the ducts showed less noise and more stability in the results. In this last (and more trustworthy) results, the calculated efficiencies are around 80%, i.e. quite close to lab measured values We would recommend using this method in the future for such measurements.

5 ACKNOWLEDGEMENTS

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