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Primary energy used in centralized and decentralized ventilation systems measured in field tests in residential buildings

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ABSTRACT

Ventilation systems can save heat energy by using heat recovery, but consume electrical energy to power the fans. In practice, the energy efficiency of those systems can be lower than expected, when compared to the nominal values provided by the manufacturer. In this paper, results of a comprehensive field tests with 20 centralized and 60 decentralized ventilation systems for residential buildings and the calculation of the primary energy savings of those devices are presented. Factors like volume flow unbalances, shortcuts, temperature change rates and specific fan power have been addressed by tracer gas technology and other means and been used as input factors to calculate the primary energy balance of those devices. Every system showed positive primary energy savings. The mean value for centralized systems was 2.92 Wh/m^3 with a high standard deviation of 2.23 Wh/m^3, while the decentralized systems showed higher savings of around 4.75 Wh/m^3 with a standard deviation of 0.01 to 0.15 Wh/m^3. In general, the calculated savings in field tests were significantly lower compared to the case of using nominal values as input parameters.

KEYWORDS

Primary Energy, Residential Ventilation, Decentralized, Centralized, Field Test

1 INTRODUCTION

Mechanical ventilation in a residential building serves two main purposes. The first being a good air quality at a given ventilation rate, avoiding over-ventilation and the second being the reduction of the primary energy used to heat the building by making use of heat recovery devices. This paper focuses on the primary energy balance of a ventilation systems and the different ways to calculate it. Savings can only be achieved, if the input of primary energy to run the ventilation system is smaller than the savings, in other words, if the net-energy-balance is positive (Roulet, 2001; Heidt, 1998). Only a complete assessment of all relevant parameters like heat recovery rate, shortcuts, specific fan power, etc. can lead to realistic calculation of the primary energy savings (Merzkirch, 2015). This calculation is often done with nominal values, derived under laboratory conditions and according to data sheets by the manufacturer. However, these nominal values can often not be reached on-site (Manz, 2000; Boerstra, 2012). An overestimation of the savings and an underestimation of the electrical energy consumed, can lead to energy demand calculations which often vary clearly from the actual energy demand of buildings (Merzkirch, 2014).

2 OBJECTS & METHODS

2.1 Types of mechanical ventilation systems

In field tests, key parameters of 20 centralized systems, installed in single-family homes and 60 decentralized devices, installed in single- and multi-family homes were assessed. The decentralized systems, installed directly in the façade of the building, were of two different kinds. The first using a regenerative heat exchanger can only be installed in pairs. Each of them uses only one fan to deliver air into the volume. While device one is transporting fresh air from outside to inside, device two is extracting air from the inside which heats up the heat storage made out of aluminium or ceramic. Every 60 seconds (the cycle time depending on the device and manufacturer) the fans switch their direction and the heat stored from the outgoing air can heat up the incoming air. The second decentralized principle is often called "single room ventilation unit". Each unit can be seen as a small centralized system since it provides supply air and extract air using a recuperative cross counterflow heat exchanger to transfer heat. The centralized systems are equipped as usual with two fans, a counterflow or cross counterflow heat exchanger and a ductwork to deliver the air at its destination. All devices come with filters for extract and outside air.

Following parameters were measured in field: Supply and extract air flow and their unbalances, internal and external shortcuts, sensitivity to pressure (decentralized units), power consumption, temperature change rate. The measurement of the flow parameters and shortcuts was done by the use of tracer gas technology, which is a commonly used method to access airflows in ventilation units and buildings (Roulet, 2008; Manz, 2001; Sandberg, 1989). The mentioned parameters above were then used to calculate the primary energy savings, expressed in Wh/m^3. This value gives us the saved primary energy per transported m^3 air in comparison to the case of natural ventilation at the same air flow. The calculations were first done with nominal values by manufacturers and then with values derived in the field tests, making a comparison possible.

2.2 Primary Energy Savings

On the negative side of the primary energy balance we find the electrical energy consumed by the ventilation device to power the fans and the electronic controls. Knowing the electrical power (P) and the delivered air flow ($\dot{V}$), one can calculate the specific fan power (SFP), which tells us, how much energy is needed to transport one m^3 of air.

$$SFP = P / \dot{V} \quad [\mathrm{Wh/m^3}] \tag{1}$$

Modern ventilation system show nominal SFP values between 0.15 [Wh/m^3] and 0.4 [Wh/m^3] (Heil, 2011, Roulet 2008). In practice, values can be higher due to high pressure losses or malfunctions (Merzkirch, 2015a; Roulet 2001).

For the measurement of the airflow $\dot{V}$, we have to consider, that possibly a part of the extract and/or exhaust air is recirculated into the supply air. The amount of fresh air is then reduced. By tracer gas measurements, this recirculation (R) was measured. For example, if 10 percent of the outgoing air was recirculated to the supply air, then value for $\dot{V}$ was also reduced by 10 percent and as a result, the SFP increases. According to manufacturer data, the internal recirculation inside the ventilation device is usually below 1 %. In field tests 17 of 20 centralized systems showed internal circulation below 1 %. The total circulation however, which consists of internal and external recirculation, which can happen within the ductwork or outside the building between outlet and inlet, was higher with a mean value of 6,5 & and a standard deviation of 12,5 % (Merzkirch, 2015a). Values in this range were also measured in other tests (Roulet, 2001; Manz, 2001) .

On the positive side of the balance, we find the savings of ventilation losses Φ_V by making use of a heat exchanger.

$$\Phi_V = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \cdot \eta_{HR} \qquad [\mathrm{Wh/m^3}] \tag{2}$$

With:
ρ densitiy of air [kg/m^3]
c_p heat capacity of air [kJ/kgK]
ΔT temperature difference between inside and outside [K]
η_{HR} efficiency of heat recovery

The density of air ρ is assumed with 1.204 kg/m^3, the specific heat capacity c_p with 1.005 kJ/(kgK). For ΔT, a mean value of 15 K was assumed. This means, that the average temperature difference in the heating period is 15 K. Therefore, the calculation of the primary energy savings counts for the energy savings on an average winter day in comparison to a natural ventilation without heat recovery.

The efficiency of the heat exchanger η_{HR} can be described by the relation of the temperature differences of exhaust/extract and exhaust/outside air. The so called temperature change rate, here called η_{real}, can be calculated as follows:

$$\eta_{real} = \frac{T_{extract} - T_{exhaust}}{T_{extract} - T_{outside}} \tag{3}$$

Of course, this relationship is a simplification, since it neglects possible enthalpy change and condensation effects. Furthermore, unbalances between supply and extract air flows can lead to over- or underestimation of the efficiency. For a more detailed discussion, see (Merzkirch, 2015a). Nominal values for η_{HR} are always based on measurements under laboratory conditions with balanced air flows. Here, values between 0.8 and 0.95 are achieved by many devices (Heil, 2011, Roulet 2008). In practice however, the measured temperature change rate is often lower with mean values around 0.58 to 0.7 (Merzkirch, 2015a; Roulet 2001).

In order to gain the primary energy instead of the end energy, where production and transportation of the energy is not included, primary energy factors are used. For electricity, we assume a factor of 2.7 ($f_{p,el}$)and for heat a factor of 1.1 ($f_{p,h}$). The production and distribution of heat on-site usually encounters losses, which we assume with 1,25 (f_h). Furthermore, a part of the heat generated by the fans is recovered in the heat exchanger. For this calculations we assume a value of 0,25 (f_{fan}). For the fan power consumption, the variable ϕ_{fan} [W] is used.

The primary energy savings can then be calculated:

$$PES = \rho \cdot c_p \cdot \Delta T \cdot \eta_{HR} \cdot f_h \cdot f_{p,h} - SFP \cdot f_{p,el} + \phi_{fan} \cdot f_{fan} \cdot f_h \cdot f_{p,h} \quad [\text{Wh/m}^3] \qquad (4)$$

3 RESULTS

In field tests of 60 decentralized and 20 centralized system, following mean values and standard deviations of the relevant parameter were obtained:

Table 1: Results of field tests – parameters relevant for energy efficiency of mechanical ventilation system.

	centralized	**decentralized (regenerative)**	**decentralized (recuperative)**	**nominal**
Specific Fan Power (SFP) [Wh/m³]	0.475 ± 0.37	0.23 ± 0.02	0.22 ± 0.01	0.15 to 0.4
Total Shortcut [%]	6.5 ± 12.5	-	13 ± 6.2	< 1
Temperature Change Rate [%]	59 ± 25	76 ± 5	80 ± 4	80 to 95

As can be seen in **Error! Reference source not found.**, the measured mean values are well below the nominal values, provided by the manufacturers. Thus, an assumption of those values, when calculating the energy demand of a building and its HVAC technology, can lead to deviations between calculation and consumption. These values are the basis for the calculation of the primary energy savings:

Table 2: Primary energy savings of 20 centralized and 60 decentralized devices, based on measured parameters according to **Error! Reference source not found.**.

	centralized	**decentralized (regenerative)**	**decentralized (recuperative)**
PES_{real} [Wh]	2.92 ± 2.23	4.67 ± 0.01	4.8 ± 0.15
$PES_{nominal}$ [Wh/m³]	5.18 ± 0.98	5.6 ± 0.01	5.4 ± 0.01

The centralized devices did not reach the nominal PES value of 5.2 Wh/m^3, but showed significantly lower values around 3 Wh/m^3. This is due to higher specific fan power values, shortcuts and lower heat exchange efficiencies, than the nominal values would let expect. But, according to the high standard deviation, there are systems, which show very high PES values above 5 Wh/m^3 and very bad systems below 1 Wh/m^3. The range is quite big and is a sign for the extraordinary importance of a thorough installation, commissioning and maintenance of such a centralized system. The users, living in a building where the systems showed low values, did not recognize the low performance of the mechanical ventilation system at all, despite of also lower indoor air quality with CO_2 values above 2500 ppm due to high shortcuts or malfunctioning fans, resulting in lower fresh air flows.

The decentralized system showed values around 4.7 to 4.8 Wh/m^3, which is closer to the nominal values of around 5.5 Wh/m^3. The simple reason for that is, that during the installation, commissioning and maintenance phase, there is less to go possibly wrong. There is no complex ductwork, no valves and the devices are easy to install and operate. However, one has to consider the higher sensitivity to pressure differences of decentralized devices. Even small differential pressure on the façade around 2.5 to 10 Pascal, which can easily be induced by wind or stack effect, can lead to serious deviations between supply and exhaust of 25 to 100 % (Merzkirch, 2015a; Manz, 2000). Such unbalances would lead to a significant decrease of heat recovery efficiency and primary energy savings. Long term measurements would be necessary to further analyse this effect.

4 CONCLUSION

In the previous chapters, the results of a comprehensive field test of 20 centralized and 60 decentralized mechanical ventilation systems in residential buildings in Luxembourg were presented. Concerning the energy efficiency of the devices, the specific fan power, shortcuts and temperature change rates were presented, leading to the calculation of the primary energy savings of the devices compared to the case of natural ventilation without heat recovery.

Concerning the specific fan power, the decentralized systems showed half the specific power around of the centralized ones. Many devices showed high volume unbalances which lead to low temperature change rates, especially for the centralized systems. But also the decentralized systems showed high sensitivity to wind and as a result, lower temperature change rates than expected. But, ventilation systems can reach high heat recovery values of 90 % if they are carefully planned, installed and operated. In almost all systems, shortcuts inside and outside the ventilation device were measured in tracer gas measurements. Shortcuts lead to a decrease of the fresh air flow and to an increase of the specific fan power.

The energy balance of those devices consists of the heat energy savings by using heat recovery on the one hand and the use of electrical energy to power the fans on the other hand. The differential of those two sides, finally gives us the primary energy savings in Wh by transported m^3 of air, on an average day during the heat period, where the temperature difference between inside and outside is 15 Kelvin. This of course, is only in comparison to the case of natural ventilation without any heat recovery.
Calculations show, that every system shows a positive primary energy balance. For centralized systems, the primary energy savings were 2.92 Wh/m^3 with a high standard deviation of 2.23. This makes clear, how important a careful planning, installation and operation is.
Decentralized systems showed higher savings of around 4.7 to 4.8 Wh/m^3 with lower standard deviations of 0.01 to 0.15. The in theory lower fan efficiency and lower heat recovery efficiency of decentralized devices do not lead to lower overall energy efficiency compared to centralized systems. Furthermore, a low specific fan power due to the lack of ductwork, easy installation and operation lead to higher mean energy efficiency than centralized systems. However, decentralized systems often show higher noise levels which can lead to unsatisfied users. They also are limited in maximum volume flow at bearable noise levels which can easily lead to an under supply of fresh air in critical situations like two persons in a bedroom of high air tightness (Merzkirch, 2015a; Manz, 2000).

However, during summertime or in times of low temperature differences between inside and outside of less than 4 Kelvin, the operation of the systems costs more energy than it is able to save (Merzkirch, 2015a). In those times, a natural ventilation is preferable. If the user is able to ventilate manually, the mechanical ventilation system could be switched off. A demand driven system would be able to automatically react to window opening and stop operating if the indoor air quality is sufficient due to low concentration of carbon dioxide (CO_2) or volatile organic compounds (VOC) (Fisk, De Almeida, 1998; Fan et al, 2014; Merzkirch, 2015b). The user can act as he pleases and the ventilation system adapts to his behaviour.

For the future, a more profound planning and installation of mechanical ventilation systems is critical if we want to lower the primary energy consumption of those systems. This especially holds true for centralized systems, were many mistakes are made during installation and hydraulic balancing. Decentralized units can play an important role in cases, where their air flow and noise comfort is sufficient. The lack of any ductwork can lead to very low specific fan power. In times, when low temperature differences between inside and outside lead to low or even negative primary energy savings, a natural ventilation, should be preferred over a mechanical one if possible and reasonable.

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