Impact of ductwork airtightness and conduction losses on heat recovery efficiency

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ABSTRACT
We have developed a simple model to estimate ductwork leakage and heat conduction losses in steady-state conditions for a balanced ventilation system. Implemented in a spreadsheet, it allows us to calculate their impact on heat recovery efficiency consistently with EN 15241 without the need for a dynamic simulation tool. One case study shows that the global heat recovery of a balanced ventilation system with a nominal heat recovery of 80% can be reduced to less than 50% if the ductwork leakage and thermal resistance are poor. These large energy impacts and today’s field data suggest that these aspects should be considered in energy performance calculations and that building professionals will have to pay particular attention to duct leakage and thermal resistance with the trend towards nearly zero-energy buildings.

KEYWORDS
ductwork, airtightness, leakage, heat conduction, heat recovery, low-energy buildings

INTRODUCTION
The EPBD recast [4] sets ambitious targets for year 2020 including the obligation for EU countries to implement regulations to increase the number of nearly zero-energy buildings (NZEB) in the next few years, and to generalize nearly zero-energy targets in new buildings and major renovations.

Previous studies (see for instance, [1][2][3][10][11][12][13]) have shown that ductwork airtightness and conduction losses are key in these types of buildings; however, to our knowledge, these losses are rarely taken into account in regulatory energy performance calculation. Probably the most detailed approach in such tools would be to fully integrate EN 15241 and 15242 ([8][9]) iterative methods for the calculation of the airflow rates taking into account envelope and ductwork leakage as well as heat conduction through duct walls. As achieved in the French energy performance regulation RT 2012, those methods can be integrated in an hourly energy calculation that includes primary energy use for heating, cooling, domestic hot water, auxiliary equipment, and lighting given specific occupation scenarios and weather conditions.
The objective of this paper is to give an overview of the underlying calculation principles for ductwork airtightness and conduction losses as well as to give estimates of the subsequent energy losses in the light of today’s objectives to generalize very-low energy buildings.

BACKGROUND
The objective of this paragraph is not to give a detailed explanation of standards EN 15241/15242, but rather to give an overview of the calculation principles.

EN 15242 allows one to calculate the airflow rates including infiltration assuming that the building or part of the building modelled can be represented by one pressure node. It takes into account the mechanical ventilation airflow rates (including ductwork leakage), opened windows, natural ventilation openings, and cracks in the envelope. The airflow rates corresponding to the two last items are characterized by a pressure difference across the components; windows opening airflow rates are calculated with the opened area, wind velocity and temperature difference. The internal pressure is solved for to reach mass equilibrium between flows entering and leaving the zone.

EN 15241 gives the characteristics of the air passing through an air treatment plant as well as the power involved for its treatment. It takes into account duct heat and leakage losses, fan power demand and the part released to the air, heat exchangers, mixing boxes, pre-heating/cooling/(de)humidification.

Two basic equations describe the physical phenomena that take place. It is possible to assess the leakage flow rate escaping through the duct walls with equation (1):

\[ q_v = K A \rho^{0.65} \]  

where \( K \) (m\(^3\) s\(^{-1}\) m\(^{-2}\) at 1 Pa) is the leakage coefficient normalized by the duct surface area (EN 12237 or EN 1507, [5][7]) and the duct surface area \( A \) (m\(^2\)) can be obtained and through EN 14239 [6].

As for conduction losses, equation (2) gives the heat flux passing through a duct:

\[ T_f - T_b = (T_i - T_b) \exp \left( \frac{U A}{Q_{ma} c_p} \right) B(T_i - T_b) \]  

where:
- \( T_f \) is the air temperature at the duct end (K);
- \( T_i \) is the air temperature at the duct entrance (K);
- \( T_b \) is the temperature of the duct surroundings (K);
- \( U \) is the U-value (thermal transmittance) of the duct (W m\(^{-2}\) K\(^{-1}\));
- \( B \) is the transmission losses fraction (-).

and the other symbols are defined in the nomenclature.

APPROACH
It is of course of interest to perform sensitivity analyses of the impact of duct leakage class or U-value on the global performance of a given building, but since it is difficult for other professionals to use these results in different contexts, the analyses would have to be reproduced with a similar software e.g. with different climates conditions,
occupation scenarios, or ventilation system types. Therefore, it requires access and sometimes customization of these software programmes, which is uneasy.

For a more generic understanding of the issues, we have developed a simplified model for a balanced ventilation system with heat recovery. The system modelled is represented schematically in Figure 1 where the symbols used are described in the nomenclature. The model assumes that the leaks are located at the air terminal devices. The objective of our development was to obtain an analytical relationship between the global efficiency of the system as a function of the leakage and conduction characteristics. For this, we assumed that the anti-freeze system, as well as the fans did not change the air temperature, i.e., \( T_{\text{af}} \approx T_{\text{ext}} \), \( T_{\text{s,exch}} \approx T_{s,\text{AHU}} \) and \( T_{r,\text{exch}} \approx T_{r,\text{AHU}} \). The global efficiency of the system is defined by:

\[
\varepsilon_{\text{glo}} = \frac{Q_{\text{ma,s}} - Q_{\text{ma,r}}}{Q_{\text{ma,r}}} \frac{T_s - T_{\text{ext}}}{T_{\text{ext}}} \tag{3}
\]

\[
T_s - T_{\text{ext}} = T_s - T_b + T_b - T_{\text{ext}} = B_s \left( T_{s,\text{exch}} - T_b \right) + \left( T_b - T_{\text{ext}} \right) \tag{4}
\]

\[
\begin{align*}
T_{s,\text{exch}} & = \tau \left( T_{r,\text{AHU}} - T_{\text{ext}} \right) \\
& = \tau \left( T_{r,\text{AHU}} - T_b + T_b - T_{\text{ext}} \right) \\
& = \tau \left( B_s \left( 1 + a_s \right) \left( T_i - T_b \right) + T_b - T_{\text{ext}} \right) \\
& = B_s \left( \tau \left( B_s \left( 1 + a_s \right) b + \left( 1 + b \right) \right) + b \right) \left( T_i - T_{\text{exch}} \right) + \left( 1 + b \right) \left( T_i - T_{\text{exch}} \right)
\end{align*} \tag{5}
\]

\[
\begin{align*}
T_b & = \tau \left( B_s \left( 1 + a_s \right) b \right) + \left( 1 + b \right) \left( 1 + \tau B_s B_r \left( 1 + a_s \right) \right)
\end{align*} \tag{6}
\]

\[
\varepsilon_{\text{glo}} = \frac{Q_{\text{ma,s}}}{Q_{\text{ma,r}}} \frac{1}{1 + a_s} \left( B_s \left( \tau \left( B_s \left( 1 + a_s \right) b + \left( 1 + b \right) \right) + b \right) \right)
\]

In the case of ducts running in unconditioned spaces well-insulated from the inside, \( b \) is close to 1 and then the ratio of the global efficiency to the nominal temperature efficiency of the heat exchanger reduces to:

\[
\frac{\varepsilon_{\text{glo}}}{\tau} = \frac{Q_{\text{ma,s}}}{Q_{\text{ma,r}}} B_s B_r
\] \tag{7}

This simple model does not provide an assessment of the global heat recovery efficiency for the building, which would need to take into account envelope leakage. However, it gives a simple equation for the system efficiency including the ductwork, which is useful to compare to the nominal efficiency of the heat exchanger. The results shown below are based on the values given in Table 1.
Figure 1. Schematic diagram of a balanced ventilation system with heat recovery. Representation is consistent with EN 15241.

Table 1. Input values used in simplified model described in Figure 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature reduction factor</td>
<td>1</td>
</tr>
<tr>
<td>Duct thermal resistance</td>
<td>Variable (1.2 or 5.0 m² K W⁻¹) (i.e., about 5 or 20 cm of insulation)</td>
</tr>
<tr>
<td>Duct leakage class</td>
<td>Variable (3 *A, A, B, C, D)</td>
</tr>
<tr>
<td>Supply duct surface area</td>
<td>12 m² (e.g. about 30 m of 125-mm ducts)</td>
</tr>
<tr>
<td>Return duct surface area</td>
<td>8 m²</td>
</tr>
<tr>
<td>Pressure difference across duct wall</td>
<td>100 Pa</td>
</tr>
<tr>
<td>Global extract and supply airflow rate in building</td>
<td>120 m³/h</td>
</tr>
<tr>
<td>Nominal efficiency of the heat exchanger</td>
<td>80%</td>
</tr>
</tbody>
</table>

RESULTS

Figure 2 shows the variation of the global energy use expressed as the ratio of the global efficiency (Equation (7)) divided by the temperature efficiency of the heat exchanger for the system described in Figure 1 and Table 1. While the nominal efficiency of the heat exchanger is 80%, the global efficiency of the system falls down to:

- 73% for a Class C system (for airtightness) with a resistance of 5 m² K / W;
- 54% for a Class C system with a resistance of 1.2 m² K / W;
- 65% for a Class A system with a resistance of 5 m² K / W;
- 50% for a Class A system with a resistance of 1.2 m² K / W;
- 53% for a system 3 times leakier than Class A with a resistance of 5 m² K / W;
- 43% for a system 3 times leakier than Class A system with a resistance of 1.2 m² K / W.

The results of the SAVE-DUCT project [1] suggest that the latest case is common in France and Belgium in terms of ductwork airtightness, and probably in many other European countries except for the Nordic region.
If the ducts are placed inside the building \((b = 0)\), there is little effect on the heat recovery efficiency. In that case, leaky ducts are detrimental to fan energy use only (which is not analyzed here) if the flow rate complies with the flows required at the air terminal devices.

This simple analysis shows the significance of the losses when a heat recovery system and the ductwork are located in an unconditioned space. When implemented in a global energy calculation method, preliminary analyses have shown that the impact can easily reach 15% of the global energy use (excluding appliances) of a very-low energy building.

**Figure 2:** Global efficiency versus nominal efficiency for various leakage classes and ductwork thermal resistance

**CONCLUSION**

Our analyses have shown that the impact of ductwork leakage and transmission losses are quite significant on the heat recovery of a whole ductwork system, as the nominal efficiency has dropped almost by a factor of 2 (from 80% to 44%) with leaky and poorly insulated ducts located in an unconditioned space. This translates into significant energy wastage that is clearly incompatible with nearly zero-energy targets. Of course, the energy use impact would be radically different with ducts inside the conditioned space or with an exhaust-only system. However, because balanced ventilation systems with ducts outside the conditioned space represent in several countries a significant market share in these types of buildings, these issues must be addressed to generalize nearly zero-energy buildings. Today’s measured field data and market knowledge on ductwork leakage and heat resistance show that
for most countries, these aspects will be a major challenge for the building industry and building professionals.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Ratio of leakage air flow rate to fan airflow rate, e.g. $a_s = \frac{Q_{ma,ls}}{Q_{ma,s}}$</td>
<td>-</td>
</tr>
<tr>
<td>$b$</td>
<td>Temperature reduction factor of buffer zone</td>
<td>-</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat capacity of air</td>
<td>J/(kg K)</td>
</tr>
<tr>
<td>$B$</td>
<td>Ratio of transmission losses</td>
<td>-</td>
</tr>
<tr>
<td>$q_v$</td>
<td>Flow rate</td>
<td>m$^3$/s$^{-1}$</td>
</tr>
<tr>
<td>$q_{vl}$</td>
<td>Leakage flow rate</td>
<td>m$^3$/s$^{-1}$</td>
</tr>
<tr>
<td>$Q_{ma}$</td>
<td>Mass airflow rate</td>
<td>kg s$^{-1}$</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Efficiency</td>
<td>-</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Temperature efficiency of heat exchanger</td>
<td>-</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Air density</td>
<td>kg m$^{-3}$</td>
</tr>
</tbody>
</table>

**Subscripts and superscripts**

- $af$: Antifreeze
- $ATD$: At air terminal device
- $b$: Pertaining to buffer zone
- $ext$: Pertaining to exterior
- $i$: Pertaining to indoor
- $lr$: Leakage on return side
- $ls$: Leakage on supply side
- $r$: Pertaining to return side
- $r,AHU$: Before fan on return side
- $r,exch$: Before heat exchanger on return side
- $s$: Pertaining to supply side
- $s,AHU$: After fan on supply side
- $s,exch$: After heat exchanger on supply side
- $glo$: Global

**REFERENCES**


