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Heat recovery ventilators and energy recovery ventilators — Method of test for performance —

Part 2:
Assessment of measurement uncertainty of performance parameters

Contents

Page

Foreword

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This document was prepared by Technical Committee ISO/TC 86, *Refrigeration and air-conditioning*, Subcommittee SC 6, *Testing and rating of air-conditioners and heat pumps*.

A list of all parts in the ISO 16494 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document is intended to be a practical guide to assist laboratory personnel in evaluating the uncertainties in the measurement of the performance of ventilators falling under the scope of ISO 16494:2014. It contains a brief introduction to the theoretical basis for the calculations, and contains examples of uncertainty budget sheets that can be used as a basis for the determination of the uncertainty of measurement.

Heat recovery ventilators and energy recovery ventilators — Method of test for performance —

Part 2:
Assessment of measurement uncertainty of performance parameters

1 Scope

This document provides guidance for practical applications of those principles in the measurement of the performance of ventilators falling under the scope of ISO 16494:2014. The references listed in the Bibliography give detailed information on the principles and theory of uncertainty as applied to measurements.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16494, *Heat recovery ventilators and energy recovery ventilators — Method of test for performance*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16494 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
calibration
operation that, under specified conditions, in a first step establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

3.2
correction
modification applied to a measured quantity value to compensate for a known systematic effect

3.3
instrumental drift
continuous change in an indication, related neither to a change in the quantity being measured nor to a change of any recognized influence quantity

3.4
resolution
smallest change in a quantity being measured that causes a perceptible change in the corresponding indication

Note 1 to entry: In the case of a digital instrument, this value corresponds to the number of digits of the reading of the instrument. This value might be different on the overall range of the instrument.

3.5
stability
ability of a measuring instrument or measuring system to maintain its metrological properties constant with time

3.6   Type of evaluation of uncertainty

3.6.1
type A evaluation of standard uncertainty
evaluation of standard uncertainty based on any valid statistical method for treating data

Note 1 to entry: Examples are calculating the standard deviation of the mean of a series of independent observations, using the method of least squares to fit a curve to data in order to evaluate the parameters of the curve and their standard deviations, and carrying out an analysis of variance in order to identify and quantify random effects in certain kinds of measurements. If the measurement situation is especially complicated, one should consider obtaining the guidance of a statistician.

3.6.2
type B evaluation of standard uncertainty
evaluation of standard uncertainty that is usually based on scientific judgment using all the relevant information available

Note 1 to entry: Relevant information can include previous measurement data, experience with, or general knowledge of, the behaviour and property of relevant materials and instruments, manufacturer's specifications, data provided in calibration and other reports, and uncertainties assigned to reference data taken from handbooks.

3.7
uncertainty due to the lack of homogeneity
component specific to air temperature measurements where several probes are used simultaneously

Note 1 to entry: In this case the air temperature value used is the mean of the measurements of the different probes.

4   Symbols

For the purposes of this document, the symbols defined in ISO 16494:2014 and the following apply.

Symbol	Description	Unit
A	Nozzle throat area	m^2
$C_{1,2,3,4}$	Tracer gas concentrations at stations 1,2,3,4	10^6
C_D	Nozzle discharge coefficient	1^{NOTE}
C_p	Specific heat of dry air	kJ/(kg K)
h	Enthalpy	kJ/kg
$NSAR$	Net supply airflow ratio	%
P_{aux}	Input power to any other electrical components in the ventilator	W
P_{em}	Input power to all electric motors in the ventilator	W
P_{in}	Input power to ventilator	W
NOTE Some quantities of dimension 1 are defined as ratios of two quantities of the same kind. The coherent derived unit is the number 1. (ISO 80000-1:2009, 3.8).		

Symbol	Description	Unit
ps	Static pressure	Pa
pv	Velocity pressure	Pa
P_v	Nozzle Pressure	Pa
P_{vma}	Power value of moving air	W
Q	Gross airflow volume	m^3/s
Q_i	Airflow rate calculated using the data from test "I" as described in ISO 16494:2014 B.2.1.1 through B.2.2.2.	m^3/s
qm_i	Air mass flow rate	kg/s
Q_{SA}	Supply airflow	m^3/s
Q_{SANet}	Net supply airflow	m^3/s
$qm_{2,net}$	Net supply mass flow rate	kg/s
t	Time	s
T	Temperature	K
V	Air volume in test chamber	m^3
v'_n	Specific Volume	m^3/kg
U	Expanded uncertainty of a measurement	Same as measurand
u	Standard uncertainty of a measurement	Same as measurand
$UEATR$	Unit exhaust air transfer ratio	%
COE	Coefficient of Energy	1[NOTE]
EW	Effective Work	W
e	Effectiveness	Ratio
ρ	Density	kg/m^3

NOTE   Some quantities of dimension 1 are defined as ratios of two quantities of the same kind. The coherent derived unit is the number 1. (ISO 80000-1:2009, 3.8).

Subscript	Description
sensible	Indicates parameter refers to sensible energy
latent	Indicates parameter refers to latent energy
total	Indicates parameter refers to total (enthalpic) energy
ducted	Indicates parameter refers to a ducted ventilator
unducted	Indicates parameter refers to an unducted ventilator
1,2,3,4	Refers to station 1, 2, 3 or 4
SA	Supply air
SANet	Net supply air

5   Explanatory notes useful in laboratory application

5.1   Uncertainty

No measurement of a real quantity can be exact; there is always some uncertainty involved in the measurement. Uncertainty may arise because of measuring instruments not being exact, because the conditions of the test are not precise, or for many other reasons, including human error. Uncertainty may be expressed as a range of test results (e.g. 10 kW ± 0,1 kW), or as a fraction or percentage of the test result (e.g. 10 kW ± 1 %).

5.2 Confidence level

Confidence level refers to the probability that the true result of a measurement lies within the range stated by the uncertainty. For example, if the measurement of a power is given as 10,0 kW ± 1 % at a confidence level of 95 %, this means that there is not more than 5 % probability that the true value of the power is outside the range 9,90 kW to 10,10 kW. A confidence level of 95 % is usually used for engineering measurements; this provides a good compromise between reliability of measurements and the cost of making those measurements.

5.3 Evaluation of uncertainties

Two types of uncertainty evaluation are recognized by ISO/IEC Guide 98-3. A type A evaluation involves statistical methods of evaluation of the uncertainties, and may only be used where there are repeated measurements of the same quantity. A type B evaluation is one using any other means, and may require the use of knowledge of the measurement system, such as calibration certificates for instruments and experience in determining what factors may produce uncertainties in the measurement.

5.4 Steps in evaluation of uncertainty in measurements

To evaluate the uncertainty in a measurement, it is necessary to follow a series of steps.

a) A mathematical model of the measurement system is developed, that lists all the factors that contribute to the measurement.

b) Examination of this model will determine the magnitude of the contribution of each source of uncertainty to the final measurement uncertainty.

c) In many cases the units of the final measurement will differ from the units of the various measurements involved. For example, the measurement of the effective work of an energy-recovery ventilator will involve measurements such as temperatures, pressures, and electrical power. In these cases, it is necessary to determine weighting factors to describe the effect that uncertainties in these measurements will have on the final measurement of capacity. These weighting factors are known as sensitivity coefficients.

d) Once all the factors contributing to the final measurement are evaluated, together with their sensitivity coefficients, they are combined to give the overall uncertainty in the final measurement.

5.5 Uncertainty of measurements

5.5.1 Uncertainty of individual measurements

The uncertainty of measurement of each individual measurement should take into account the different components of uncertainties as described below, where appropriate.

Table 1 — Components of uncertainties for individual measurements

Source of un-certainty	Evaluation basis	Value from calibration certificate or actual value	Probability distribution	Coverage factor, k (ISO/IEC Guide 99:2007, 2.38)[a]	Standard uncertainty
Calibration	Calibration certificate	U_1	Normal	2	$u_1 = \dfrac{U_1}{2}$
Resolution	Specifications	U_2	Rectangular	$2 \times \sqrt{3}$	$u_2 = \dfrac{U_2}{2 \times \sqrt{3}}$
Correction	Calibration certificate	U_3	— (see 5.5.1 NOTE 1 and NOTE 2)	— (see 5.5.1 NOTE 1 and NOTE 2)	u_3 (see 5.5.1 NOTE 1 and NOTE 2)
Drift	Calibration certificate	U_4	Rectangular	$\sqrt{3}$	$u_4 = \dfrac{U_4}{\sqrt{3}}$
Stability (in time)	Mean	S_5	Standard deviation on a mean value	$\sqrt{N_T}$	$s_5 = \dfrac{S_5}{\sqrt{N_T}}$

[a] Number larger than one by which a combined standard measurement uncertainty is multiplied to obtain an expanded measurement uncertainty.

The expanded uncertainty, U, is thus calculated as follows.

a) If the calibration correction is applied:

$$U = 2 \times \sqrt{u_1{}^2 + u_2{}^2 + u_3{}^2 + u_4{}^2 + u_i{}^2 + \left(\frac{S_5}{\sqrt{N_T}}\right)^2} \qquad (1)$$

NOTE 1   If the calibration correction value U_3 is applied directly, then the evaluated value of $u_3 = 0$. In case that the averaged value of deviations at several calibration points is applied as correction factor, the value of u_3 arising from incomplete correction is evaluated from the variance of deviations remaining after the correction value has been applied to each calibration data.

b) If the calibration correction is not applied:

$$U = 2 \times \sqrt{u_1{}^2 + u_2{}^2 + u_4{}^2 + u_i{}^2 + \left(\frac{S_5}{\sqrt{N_T}}\right)^2} + U_3 \qquad (2)$$

NOTE 2   Avoid calculating the expanded uncertainty without applying the correction. However, if the correction value is small compared to the uncertainty, it could be decided that correction is not needed. If the value of the calibration correction U_3 is entered in Formula (2), then $u_3 = 0$.

5.5.2 Uncertainty of a mean value from several measurements

If several sensors are used for determining a mean value, this mean value is calculated with the following formula:

$$T_{\mathrm{m}} = \frac{\sum_{i=1}^{N} T_{\mathrm{i}}}{N} \tag{3}$$

where

T_{m} is the mean value;

T_{i} is the value measured by the sensor i;

N is the number of sensors.

The uncertainty of this mean value should be calculated from the uncertainty of each individual measurement to which an additional component for homogeneity is added as follows, assuming the individual measurements to be correlated:

$$u(T_{\mathrm{m}}) = \sqrt{\left(\frac{\sum_{i=1}^{N} u(T_{\mathrm{i}})}{N}\right)^2 + \left(\frac{s}{\sqrt{N}}\right)^2}$$

leading to:

$$U(T_{\mathrm{m}}) = 2 \times u(T_{\mathrm{m}}) = 2 \times \sqrt{\left(\frac{\sum_{i=1}^{N} u(T_{\mathrm{i}})}{N}\right)^2 + \left(\frac{s}{\sqrt{N}}\right)^2} = 2 \times \sqrt{\left(\frac{\sum_{i=1}^{N} U(T_{\mathrm{i}})}{2 \times N}\right)^2 + \left(\frac{s}{\sqrt{N}}\right)^2} \tag{4}$$

where

$u(T_{\mathrm{m}})$ is the combined standard uncertainty on the mean value;

$U(T_{\mathrm{m}})$ is the expanded uncertainty on the mean value (k = 2, confidence level approximately 95 %);

$u(T_{\mathrm{i}})$ is the standard measurement uncertainty of the sensor i, determined according to Table 1;

$U(T_{\mathrm{i}})$ is the expanded measurement uncertainty of the sensor i, determined according to Table 1;

s is the standard deviation on the mean value (calculating from the N individual measurements, T_{i}).

NOTE 1   According to ISO/IEC Guide 98-3:2008, 5.2.2 NOTE 1, for the very special case where all of the input estimates are correlated with correlation coefficients equal to +1, the uncertainty of measurements with the following formula:

$$u_{\mathrm{c}}^2(y) = \left(\sum_{i=1}^{N} c_{\mathrm{i}} u(x_{\mathrm{i}})\right)^2$$

Leads to, for the mean value, $(T_{\mathrm{m}}) = \dfrac{\sqrt{\left(\sum_{i-1}^{N} u(T_{\mathrm{i}})\right)^2}}{N} = \sqrt{\left(\dfrac{\sum_{i-1}^{N} u(T_{\mathrm{i}})}{N}\right)^2}$ \hfill (5)

NOTE 2   See ISO 3534-1 for guidance in evaluating the uncertainty of the mean value obtained from repeated measurements of the same parameter.

5.5.3 Uncertainty of a value obtained by using a smoothing curve

If a value, $V(m)$, is determined from a measurement m and the use of a smoothing curve, then the term:

$$u^2\left(V\left(m\right)\right)$$

should be replaced by:

$$\left[\left(\frac{\partial V}{\partial m}|m_i\right)^2 \cdot u^2\left(m_i\right) + u^2_{smooth}\left(V\left(m\right)\right)\right] \tag{6}$$

where

$\qquad u(m_i)$ $\qquad$ is the standard uncertainty on each measurement m_i (determined according to [Table 1](#));

$\qquad u_{smooth}(V(m))$ $\qquad$ is the standard uncertainty component due to the smoothing of the law. Usually, this term is evaluated as the maximum deviation between the smoothing curve and the experimental measurements;

$\qquad \dfrac{\partial V}{\partial m}|m_i$ $\qquad$ is the derivative of the smoothing curve with respect to measurement m_i.

6 Evaluation of uncertainty

6.1 Airflow performance

6.1.1 Air volume flow rate

6.1.1.1 Measured parameters affecting the measurement

— Discharge coefficient;

— Nozzle throat area;

— Nozzle pressure;

— Specific volume.

6.1.1.2 Air volume flow rate measurement

Air volume flow rate is calculated as follows:

$$Q = C_D A\sqrt{2 P_v v'_n} \tag{7}$$

where

$\qquad C_D$ $\qquad$ is the nozzle(s) discharge coefficient (dimensionless);

$\qquad A$ $\qquad$ is the nozzle(s) throat area (m^2);

$\qquad P_v$ $\qquad$ is the nozzle pressure (Pa);

$\qquad v'_n$ $\qquad$ is the specific volume (m^3/kg).

6.1.1.3 Uncertainty calculation — Specific case

When the air volume flow rate is determined by using a nozzle chamber, the calculation of the relative uncertainty of measurement is made as follows:

$$\left(\frac{u(Q)}{Q}\right)^2 = \left(\frac{u(C_D)}{C_D}\right)^2 + \left(\frac{u(A)}{A}\right)^2 + \left(\frac{u(p_v)}{2p_v}\right)^2 + \left(\frac{u(v'_n)}{2v'_n}\right)^2 \tag{8}$$

When the air volume flow rate is determined by using a nozzle chamber, the calculation of the absolute uncertainty of measurement is made as follows:

$$\left(u(Q)\right)^2 = \left(u(C_D)A\sqrt{2p_v v'_n}\right)^2 + \left(u(A)C_D\sqrt{2p_v v'_n}\right)^2 +$$

$$\left(\frac{u(p_v)C_D A\sqrt{2p_v v'_n}}{2p_v}\right)^2 + \left(\frac{u(v'_n)C_D A\sqrt{2p_v v'_n}}{2v'_n}\right)^2 \tag{9}$$

6.1.2 Air mass flow rate

6.1.2.1 Measured parameters affecting the measurement

— Air volume flow rate;

— Air density.

6.1.2.2 Air mass flow rate

When mass flow rates are calculated, they can be determined from the relevant air volume flow rate by the following formula:

$$qm_i = Q_i \rho_i \tag{10}$$

where

qm_i is the relevant air volume flow rate i (m³/s);

ρ_i is the density of air stream i (kg/m³).

6.1.2.3 Uncertainty calculation — General case

$$u(qm_i)^2 = \left(u(Q_i)\rho_i\right)^2 + \left(u(\rho_i)Q_i\right)^2 \tag{11}$$

6.1.3 Static pressure differential

6.1.3.1 Measured parameters affecting the measurement

— Inlet pressure;

— Outlet pressure.

6.1.3.2 Static pressure differential

Static pressure differential is described by the following formulae:

$$ps_{2-1} = |ps_2 - ps_1| \tag{12}$$

$$ps_{4-3} = \left| ps_4 - ps_3 \right| \tag{13}$$

where ps_n is the static pressure at station n (Pa).

6.1.3.3 Uncertainty calculation — General case

$$u\left(ps_{2-1}\right)^2 = \left(u\left(ps_2\right)\right)^2 + \left(u\left(ps_1\right)\right)^2 \tag{14}$$

$$u\left(ps_{4-3}\right)^2 = \left(u\left(ps_4\right)\right)^2 + \left(u\left(ps_3\right)\right)^2 \tag{15}$$

6.2 Unit exhaust air transfer ratio

6.2.1 Measured parameters affecting test results

— Tracer gas concentrations.

6.2.2 UEATR measurement

The unit exhaust air transfer ratio is calculated as follows:

$$UEATR = \frac{C_2 - C_1}{C_3 - C_1} \times 100 \tag{16}$$

where

$UEATR$ is the unit exhaust air transfer ratio (%);

C_1 is the tracer gas concentration at entering supply air(station 1);

C_2 is the tracer gas concentration at leaving supply air (station 2);

C_3 is the tracer gas concentration at entering exhaust air (station 3).

6.2.3 Uncertainty calculation — General case

The uncertainty calculation is given by the general formula:

$$u\left(UEATR\right)^2 = \left[\left(\frac{u(C_2)}{(C_3 - C_1)}\right) \times 100\right]^2 + \left[\left(\frac{(C_2 - C_1)}{(C_3 - C_1)} - \frac{(C_2 - C_1 + u(C_1))}{(C_3 - C_1 + u(C_1))}\right) \times 100\right]^2 +$$
$$\left[\left(\frac{(C_2 - C_1)}{(C_3 - C_1)} - \frac{(C_2 - C_1)}{(C_3 - u(C_3) - C_1)}\right) \times 100\right]^2 \tag{17}$$

6.3 Net supply airflow

6.3.1 Net supply airflow ducted units

6.3.1.1 Measured parameters affecting test results

— $UEATR$;

— Supply airflow.

6.3.1.2   NSAR measurement

Net supply airflow for ducted units is calculated as follows:

$$Q_{\text{SANet}} = \frac{NSAR}{100} \times Q_{\text{SA}}$$ (18)

where

Q_{SANet} is the net supply airflow (m³/s);

Q_{SA} is the supply airflow (m³/s);

$NSAR$ is the net supply airflow ratio (%).

where

$$NSAR = 100 - EATR$$ (19)

and

$UEATR$ is the unit exhaust air transfer ratio (%).

6.3.1.3   Uncertainty calculation for ducted units — General case

$$u\left(Q_{\text{SANet}}\right)^2 = \left(\frac{u\left(UEATR\right)}{100} \times Q_{\text{SA}}\right)^2 + \left(\frac{\left(100 - UEATR\right)}{100} \times u\left(Q_{\text{SA}}\right)\right)^2$$ (20)

6.3.2   Net supply airflow unducted ventilators

6.3.2.1   Measured parameters affecting test results

— Chamber volume;

— Tracer gas concentration;

— Time.

6.3.2.2   NSAR measurement

Net supply airflow for unducted ventilators is calculated as follows:

$$Q_{\text{SANet}} = Q_1 - Q_2$$ (21)

where

$$Q_{\text{i}} = \frac{V}{t} \ln \frac{\left(C_{\text{i}} - C_{\text{o}}\right)}{\left(C_{\text{t}} - C_{\text{o}}\right)}$$ (22)

where, when corrected to standard temperature and density:

Q_{SANet} is the net supply airflow (m³/s);

Q_1 is the average of the three calculated overall airflow rates with the unit under test in operation as described in ISO 16494:2014 B.2.1.1 and B.2.1.2 (m³/s);

Q_2 is the average of the three calculated natural airflow rates of the test chamber with the ventilator removed as described in ISO 16494:2014 B.2.2.1 and B.2.2.2 (m³/s);

Q_i is the airflow rate calculated using the data from a test 'i' as described in ISO 16494:2014 B.2.1.1, B.2.1.2, B.2.2.1 and B.2.2.2 (m³/s);

V is the air volume in the test chamber (m³);

t is the length of time elapsed since the start of test unit operation (s);

C_i is the initial tracer gas concentration in the test chamber (average of all measurement points);

C_o is the tracer gas concentration in outdoor air (station 1);

C_t is the tracer gas concentration in the test chamber after t seconds (average of all measurement points).

6.3.2.3 Uncertainty calculation for unducted units — General case

$$u(Q_{SANet})^2 = u(Q_1)^2 + u(Q_2)^2 \tag{23}$$

General uncertainty formula for Q_i:

$$u(Q_i)^2 = \left(\frac{u(V)}{t} ln \frac{(C_i - C_o)}{(C_t - C_o)} \right)^2 + \left(\frac{u(t)V}{t^2 - u(t)t} ln \frac{(C_i - C_o)}{(C_t - C_o)} \right)^2 + \left(\frac{V}{t} \left(ln \frac{(C_i - C_o)}{(C_i - u(C_i) - C_o)} \right) \right)^2 +$$

$$\left(\frac{V}{t} \left(ln \frac{(C_i - C_o)(C_t - C_o + u(C_o))}{(C_t - C_o)(C_i - C_o + u(C_o))} \right) \right)^2 + \left(\frac{V}{t} \left(ln \frac{((C_t - u(C_t) - C_o))}{(C_t - C_o)} \right) \right)^2 \tag{24}$$

6.4 Gross effectiveness

6.4.1 Measured parameters affecting the measurement

— Dry-bulb temperature;

— Absolute humidity;

— Enthalpy.

6.4.2 Gross effectiveness measurement

The gross sensible, latent or total effectiveness of an HRV or ERV at test conditions is calculated by the following formula:

$$\varepsilon = \frac{x_1 - x_2}{x_1 - x_3} \tag{25}$$

where x equals one of the following for the test condition under consideration:

- x is the dry-bulb temperature (for sensible effectiveness), °C; or

- x is the absolute humidity ratio (for latent effectiveness), kg water/kg dry air; or

- x is the total enthalpy (for total effectiveness), J/kg.

6.4.3 Uncertainty calculation — General case

$$u(\varepsilon)^2 = \left[\left(\frac{x_1 - x_2}{x_1 - x_3} - \frac{\left(x_1 - u(x_1) - x_2\right)}{\left(x_1 - u(x_1) - x_3\right)}\right)\right]^2 + \left[\frac{\left(u(x_2)\right)}{\left(x_1 - x_3\right)}\right]^2 + \left[\left(\frac{x_1 - x_2}{x_1 - x_3} - \frac{\left(x_1 - x_2\right)}{\left(x_1 - x_3 - u(x_3)\right)}\right)\right]^2 \quad (26)$$

6.5 Coefficient of energy

6.5.1 Coefficient of energy: Ducted ventilators

6.5.1.1 Measured parameters affecting the measurement

— Enthalpy;

— Net supply mass flow rate at station 2;

— Unit exhaust air transfer ratio;

— Specific volume of supply air at station 2;

— Static pressure;

— Dynamic pressure;

— Input power.

6.5.1.2 Coefficient of Energy — Measurement

The coefficient of energy (COE) of a ducted ventilator is described by the following formula:

$$COE_{\text{ducted}} = \frac{\left(\left|qm_{2,\text{net}}\left(h_1 - h_2\right)\right| \times 1\,000\right) + P_{\text{vma}}}{P_{\text{in}}} \quad (27)$$

where

h_1 is the enthalpy of the air at station 1 (kJ/kg of dry air);

h_2 is the enthalpy of the air at station 2 (kJ/kg of dry air);

$qm_{2,\text{net}}$ is the net supply mass flow rate at station 2 (kg/s);

P_{vma} is the power value of moving air (J/s);

P_{in} is the input power to ventilator (W).

and

$$qm_{2,\text{net}} = qm_2 \left(1 - \frac{UEATR}{100} \right)$$

(28)

and

$$P_{\text{vma}} = \left(\sum_{n=1}^{4} |ps_n + pv_n| \right) 2qm_{2,\text{net}} v_s$$

(29)

where

v_s is the specific volume of the supply air (m³/kg);

ps_n is the external static pressures at the inlet(s) and outlet(s) (Pa);

pv_n is the dynamic pressure at the inlet(s) and outlet(s) (Pa).

and

$$P_{in} = P_{em} + P_{aux}$$

(30)

where

P_{em} is the input power to all electric motors in the ventilator (W);

P_{aux} is the input power to any other electrical components in the ventilator (W).

6.5.1.3 Uncertainty calculation — General case

$$u\left(COE_{\text{ducted}}\right)^2 = \left(\frac{\left(u(qm_{2,\text{net}})\right)(h_2 - h_1) \times 1\,000}{P_{in}} \right)^2 + \left(\frac{qm_{2,\text{net}}\left(u(h_2)\right) \times 1\,000}{P_{in}} \right)^2 +$$
$$\left(\frac{qm_{2,\text{net}}\left(u(h_1)\right) \times 1\,000}{P_{in}} \right)^2 + \left(\frac{u(P_{\text{vma}})}{P_{in}} \right)^2 + \left(\frac{-u(P_{in})\left\{ |qm_{2,\text{net}}(h_2 - h_1)| \times 1\,000 + P_{\text{vma}} \right\}}{P_{in}^2 - u(P_{in})P_{in}} \right)^2$$

(31)

where

$$u\left(qm_{2,\text{net}}\right)^2 = \left(u(qm_2)\left(1 - \frac{UEATR}{100}\right) \right)^2 + \left(qm_2\left(\frac{u(UEATR)}{100}\right) \right)^2$$

(32)

and

$$\left(u\left(P_{\text{vma}}\right)\right)^2 = \sum_{n=1}^{4} \left(u(ps_n)2qm_{2,Net}v_s\right)^2 + \sum_{n=1}^{4} \left(u(pv_n)2qm_{2,Net}v_s\right)^2 +$$
$$\left(\sum_{n=1}^{4} |ps_n + pv_n|2u(qm_{2,Net})v_s \right)^2 + \left(\sum_{n=1}^{4} |ps_n + pv_n|2qm_{2,Net}u(v_s) \right)^2$$

(33)

and

$$u\left(P_{in}\right)^2 = u\left(P_{em}\right)^2 + u\left(P_{aux}\right)^2$$

(34)

6.5.1.4 Uncertainty calculation — Specific case

When moisture transfer is not of interest (sensible-only ventilators) or does not occur the substitution described in ISO 16494:2014, 8.7.3 can be made.

$$u\left(COE_{\text{ducted}}\right)^2 = \left(\frac{\left(u\left(qm_{2,\text{net}}\right)C_p\left(T_2-T_1\right)\times 1\,000\right)}{P_{\text{in}}}\right)^2 + \left(\frac{\left(qm_{2,\text{net}}C_p\left(u\left(T_2\right)\right)\times 1\,000\right)}{P_{\text{in}}}\right)^2 +$$

$$\left(\frac{\left(qm_{2,\text{net}}C_p\left(u\left(T_1\right)\right)\times 1\,000\right)}{P_{\text{in}}}\right)^2 + \left(\frac{u\left(P_{\text{vma}}\right)}{P_{\text{in}}}\right)^2 +$$

$$\left(\frac{-u\left(P_{\text{in}}\right)\left\{\left|qm_{2,\text{net}}C_p\left(T_2-T_1\right)\right|\times 1\,000 + P_{\text{vma}}\right\}}{P_{\text{in}}^2 - u\left(P_{\text{in}}\right)P_{\text{in}}}\right)^2 +$$

$$\left(\frac{\left(qm_{2,\text{net}}\cdot u\left(C_p\right)\left(T_2-T_1\right)\times 1000\right)}{P_{\text{in}}}\right)^2 \tag{35}$$

6.5.2 Coefficient of energy — Unducted ventilators

6.5.2.1 Measured parameters affecting the measurement

— Enthalpy;

— Net supply mass flow rate at station 2;

— Unit exhaust air transfer ratio;

— Specific volume of supply air at station 2;

— Input power.

6.5.2.2 Coefficient of energy — Measurement

The coefficient of energy (COE) of an unducted ventilator is described by the following formula:

$$COE_{\text{unducted}} = \frac{\left|qm_{2,\text{net}}\left(h_1-h_2\right)\right|\times 1\,000}{P_{\text{in}}} \tag{36}$$

where

h_1 is the enthalpy of the air at station 1 (kJ/kg of dry air);

h_2 is the enthalpy of the air at station 2 (kJ/kg of dry air);

$qm_{2,\text{net}}$ is the net supply mass flow rate (kg/s);

P_{in} is the input power to ventilator (W).

and

$$qm_{2,\text{net}} = qm_2 \left(1 - \frac{UEATR}{100} \right) \tag{37}$$

and

$$P_{\text{in}} = P_{\text{em}} + P_{\text{aux}} \tag{38}$$

where

P_{em} is the input power to all electric motors in the ventilator (W);

P_{aux} is the input power to any other electrical components in the ventilator (W).

6.5.2.3 Uncertainty calculation — General case

$$u\left(COE_{\text{unducted}}\right)^2 = \left(\frac{\left(u\left(qm_{2,\text{net}}\right)\left(h_2 - h_1\right) \times 1\,000\right)}{P_{\text{in}}} \right)^2 + \left(\frac{\left(qm_{2,\text{net}}\left(u\left(h_2\right)\right) \times 1\,000\right)}{P_{\text{in}}} \right)^2 +$$

$$\left(\frac{\left(qm_{2,\text{net}}\left(u\left(h_1\right)\right) \times 1\,000\right)}{P_{\text{in}}} \right)^2 + \left(\frac{u\left(P_{\text{in}}\right)qm_{2,\text{net}}\left(h_2 - h_1\right) \times 1\,000}{P_{\text{in}}^2 - u\left(P_{\text{in}}\right)P_{\text{in}}} \right)^2 \tag{39}$$

where

$$u\left(qm_{2,\text{net}}\right)^2 = \left(u\left(qm_2\right)\left(1 - \frac{UEATR}{100}\right) \right)^2 + qm_2 \left(\frac{u\left(UEATR\right)}{100} \right)^2 \tag{40}$$

and

$$u\left(P_{\text{in}}\right)^2 = u\left(P_{\text{em}}\right)^2 + u\left(P_{\text{aux}}\right)^2 \tag{41}$$

6.5.2.4 Uncertainty calculation — Specific case

When moisture transfer is not of interest (sensible-only ventilators) or does not occur, the substitution described in ISO 16494:2014, 8.7.3 can be made.

$$u\left(COE_{\text{unducted,sensible}}\right)^2 = \left(\frac{\left(u\left(qm_{2,\text{net}}\right)c_{\text{p}}\left(T_2 - T_1\right) \times 1\,000\right)}{P_{\text{in}}} \right)^2 +$$

$$\left(\frac{\left(qm_{2,\text{net}}c_{\text{p}}\left(u\left(T_2\right)\right) \times 1\,000\right)}{P_{\text{in}}} \right)^2 + \left(\frac{\left(qm_{2,\text{net}}c_{\text{p}}\left(u\left(T_1\right)\right) \times 1\,000\right)}{P_{\text{in}}} \right)^2 +$$

$$\left(\frac{-u\left(P_{\text{in}}\right)qm_{2,\text{net}}c_{\text{p}}\left(T_2 - T_1\right) \times 1\,000}{P_{\text{in}}^2 - u\left(P_{\text{in}}\right)P_{\text{in}}} \right)^2 + \left(\frac{qm_{2,\text{net}}u\left(C_{\text{p}}\right)\left|T_2 - T_1\right| \times 1\,000}{P_{\text{in}}} \right)^2 \tag{42}$$

6.6   Effective work (EW)

6.6.1   Measured parameters affecting the measurement

— COE;

— $P_\text{in.}$

6.6.2   Effective work: Ducted or unducted ventilators

The effective work (EW) of a ducted or unducted ventilator is described by the following formula:

$$EW = P_\text{in} \times (COE - 1) \tag{43}$$

6.6.3   Uncertainty calculation — General case

$$u(EW)^2 = \left(u(P_\text{in}) \times (COE - 1)\right)^2 + \left(P_\text{in} \times u(COE)\right)^2 \tag{44}$$

6.6.4   Uncertainty calculation — Specific case

When moisture transfer is not of interest (sensible-only ventilators) or does not occur, the substitution described in ISO 16494:2014, 8.7.3 can be made.

$$u(EW_\text{sensible})^2 = \left(u(P_\text{in}) \times (COE_\text{sensible} - 1)\right)^2 + \left(P_\text{in} \times u(COE_\text{sensible})\right)^2 \tag{45}$$

Annex A
(informative)

Uncertainty budget sheets

The following (18) budget sheets, presented as tables, are given in this annex as an example of uncertainty calculations using an uncertainty budget sheet approach.

— Table A.1 — Uncertainty budget sheet for air volume flow rate Q

— Table A.2 — Uncertainty budget sheet for air mass flow rate qm_i

— Table A.3 — Uncertainty budget sheet for static pressure differential(s) $ps_{2\text{-}1}$, $ps_{4\text{-}3}$

— Table A.4 — Uncertainty budget sheet for unit exhaust air transfer ratio $UEATR$

— Table A.5 — Uncertainty budget sheet for net supply airflow Q_{SANet}

— Table A.6 — Uncertainty budget sheet for net supply mass airflow $qm_{2,net}$

— Table A.7 — Uncertainty budget sheet for power value of moving air P_{vma}

— Table A.8 — Uncertainty budget sheet for gross effectiveness, sensible $\varepsilon_{sensible}$

— Table A.9 — Uncertainty budget sheet for gross effectiveness, latent ε_{latent}

— Table A.10 — Uncertainty budget sheet for gross effectiveness, total ε_{total}

— Table A.11 — Uncertainty budget sheet for coefficient of energy, ducted ventilator, total COE_{ducted}

— Table A.12 — Uncertainty budget sheet for coefficient of energy, ducted ventilator, sensible $COE_{ducted,sensible}$

— Table A.13 — Uncertainty budget sheet for coefficient of energy, unducted ventilator, total $COE_{unducted}$

— Table A.14 — Uncertainty budget sheet for coefficient of energy, unducted ventilator, sensible $COE_{unducted,sensible}$

— Table A.15 — Uncertainty budget sheet for effective work, total EW

— Table A.16 — Uncertainty budget sheet for effective work, sensible $EW_{sensible}$

— Table A.17 — Uncertainty budget sheet for airflow rate from test i, used to determine net supply airflow for unducted ventilators using the attenuation method Q_i

— Table A.18 — Uncertainty budget sheet for net supply airflow Q_{SANet} for unducted ventilators using the attenuation method

In the normative sections of this document, most of the numbered formulae for determination of uncertainty yield the absolute uncertainty $u(Q)$.

The following budget sheets yield first the relative uncertainty $u(Y)/Y$, and the absolute uncertainty $u(Q)$ is calculated by multiplying the value of Q by $u(Y)/Y$.

Alternate forms of the formulae which yield the relative uncertainty $u(Y)/Y$ are shown in the tables and are labelled as "(rel)".

These budget sheets are only an example of the budget sheet method of calculation for guidance. Laboratories may use appropriate data depending on the test methods and instrumentation used. For minimum uncertainty in test results it is essential that an appropriate method is adopted for each test.

If the functional relationship is a product or quotient, i.e. the output quantity is obtained from only the multiplication or division of the input quantities, this can be transformed to a linear addition by the use of relative values.

In all cases of the general form $Y = c\, X_1^{p1} X_2^{p2} ... X_N^{pN}$ in which the exponents p_i are known positive or negative numbers having negligible uncertainties, then the combined standard relative uncertainty $u(Y)/Y$ can be calculated from the relative standard uncertainty of all of the sources of uncertainty as follows (see ISO/IEC Guide 98-3:2008, 5.1.6):

$$\frac{u(Y)}{|Y|} = \sqrt{\sum_{i=}^{n}\left[\frac{p_i u(x_i)}{|x_i|}\right]^2} \qquad\qquad (A.1)$$

Table A.1 — Uncertainty budget sheet for air volume flow rate Q

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Measured value	Uncertainty of each factor				Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{|x_i|}$	
				Expanded uncertainty	Probability distribution	Divisor	Standard uncertainty $u(x_i)$		
Nozzle Coefficient	C_D	—	0,909	0,001	Normal	2	0,000 5	$\dfrac{u(C_D)}{\lvert C_D\rvert}$	0,055 %
Nozzle Area	A	m^2	0,005	0,000 1	Normal	2	0,000 05	$\dfrac{u(A)}{\lvert A\rvert}$	1,00 %
Nozzle Pressure	Pv	Pa	124,6	2,5	Normal	2	1,25	$\dfrac{u(P_v)}{\lvert 2P_v\rvert}$	0,502 %
Specific Volume	v'_n	m^3/kg	0,868 8	0,011	Normal	2	0,005 5	$\dfrac{u(V'_n)}{\lvert 2V'_n\rvert}$	0,317 %
Air volume flow rate	Q	m3/s	0,065 0	← calculated value per Formula (7)					

Combined standard relative uncertainty $u(Y)/Y$	By uncertainty budget	1,16 %
Expanded absolute uncertainty $U(Q)$		0,001 55
Expanded relative uncertainty $U(Y)/Y$		2,32 %
Combined standard relative uncertainty $u(Y)/Y$	By formula at left	1,16 %
Expanded relative uncertainty $U(Y)/Y$		2,32 %
For expanded uncertainty, coverage factor $k = 2$		

Formula (7)

$$Q = C_D\, A \sqrt{2 P_v\, v'_n}$$

(rel)

$$\left(\frac{u(Q)}{Q}\right)^2 = \left(\frac{u(C_D)}{C_D}\right)^2 + \left(\frac{u(A)}{A}\right)^2 + \left(\frac{u(P_v)}{2P_v}\right)^2 + \left(\frac{u(v'_n)}{2v'_n}\right)^2$$

Table A.2 — Uncertainty budget sheet for air mass flow rate qm_1

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Uncertainty of each factor				Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i \rvert}$
			Measured value	Expanded uncertainty	Probability distribution	Divisor		
Air volume flow rate	Q_i	m³/s	0,066 9	0,001 55	Normal	2	0,000 775	$\dfrac{u(Q_i)}{\lvert Q_i \rvert}$ 1,16 %
Air density as tested	ρ_i	kg/m³	1,151	,015	Normal	2	0,007 5	$\dfrac{u(\rho_i)}{\lvert \rho_i \rvert}$ 0,65 %
Air mass flow rate	qm_i	**kg/s**	**0,077 0**	← calculated value per **Formula (10)**				

Formula (10)

$$qm_i = Q_i \rho_i$$

(rel)

$$\left(\frac{u(qm_i)}{qm_i}\right)^2 = \left(\frac{u(Q_i)}{Q_i}\right)^2 + \left(\frac{u(\rho_i)}{\rho_i}\right)^2$$

Combined standard relative uncertainty $u(Y)/Y$	By uncertainty budget	1,33 %
Expanded absolute uncertainty $U(Q)$		0,002 05
Expanded relative uncertainty $U(Y)/Y$		2,66 %
Combined standard relative uncertainty $u(Y)/Y$	By formula at left	1,33 %
Expanded relative uncertainty $U(Y)/Y$		2,66 %
For expanded uncertainty, coverage factor $k = 2$		

Table A.3 — Uncertainty budget sheet for static pressure differential ps_{2-1}

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Measured value	Uncertainty of each Factor			Value of standard uncertainty $u(x_i)$	Standard uncertainty of each value $u_c^2(y) = \left(\displaystyle\sum_{i=1}^N c_i u(x_i)\right)^2$	
				Expanded uncertainty	Probability distribution	Divisor			
Inlet pressure	ps_1	Pa	20	2,5	Normal	2	1,250	$u(ps_1)$	1,250
Outlet pressure	ps_2	Pa	30	2,5	Normal	2	1,250	$u(ps_2)$	1,250
Static pressure differential	ps_{2-1}	**Pa**	**50**	←calculated value per Formula (12)					
								Combined standard uncertainty $u_c(Q)$	1,768
						By uncertainty budget		Expanded absolute uncertainty $U(Q)$	3,535
								For expanded uncertainty, coverage factor k = 2	

Formula (12)	$ps_{2-1} = \left\| ps_2 - ps_1 \right\|$	(see ISO/IEC Guide 98-3:2008, 5.1.5)

Table A.4 — Uncertainty budget sheet for unit exhaust air transfer ratio *UEATR*

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Measured value	Uncertainty of each factor			Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i \rvert}$
				Expanded uncertainty	Probability distribution	Divisor		
Tracer gas concentration entering supply air (station 1)	C_1	10^6	84	1	Normal	2	0,5	$\left\lvert 1-\dfrac{(C_2-C_1-u(C_1))(C_3-C_1)}{(C_3-C_1-u(C_1))(C_2-C_1)}\right\rvert$ — 1,3 %
Tracer gas concentration entering supply air (station 2)	C_2	10^6	121	1	Normal	2	0,5	$\left\lvert\dfrac{u(C_2)}{C_2-C_1}\right\rvert$ — 1,4 %
Tracer gas concentration entering supply air (station 3)	C_3	10^6	824	1	Normal	2	0,5	$\left\lvert 1-\dfrac{(C_3-C_1)}{(C_3-C_1-u(C_3))}\right\rvert$ — 0,07 %
Unit Exhaust Air Transfer Rate	**UEATR**	%	**5,0**					← calculated value per Formula (16)

Formula (16):

$$UEATR = \left\lvert \frac{C_2-C_1}{C_3-C_1} \times 100 \right\rvert$$

(rel):

$$\left(\frac{u(UEATR)}{UEATR}\right)^2 = \left(\frac{u(C_2)}{C_2-C_1}\right)^2 + \left(1-\frac{(C_2-C_1-u(C_1))(C_3-C_1)}{(C_3-C_1-u(C_1))(C_2-C_1)}\right)^2 + \left(1-\frac{(C_3-C_1)}{(C_3-C_1-u(C_3))}\right)^2$$

By uncertainty budget:

Combined standard relative uncertainty $u(Y)/Y$	1,9 %
Expanded absolute uncertainty $U(Q)$	0,19
Expanded relative uncertainty $U(Y)/Y$	3,8 %

By formula at left:

Combined standard relative uncertainty $u(Y)/Y$	1,9 %
Expanded relative uncertainty $U(Y)/Y$	3,8 %

For expanded uncertainty, coverage factor $k = 2$

Table A.5 — Uncertainty budget sheet for net supply airflow Q_{SANet}

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Uncertainty of each factor				Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{|x_i|}$	
			Measured value	Expanded uncertainty	Probability distribution	Divisor			
Supply airflow	Q_{SA}	m³/s	0,066 9	0,001 6	Normal	2	0,001	$\dfrac{u(Q_{SA})}{|Q_{SA}|}$	1,17 %
UEATR	UEATR	%	5,000	0,019 0	Normal	2	0,010	$\dfrac{u(UEATR)}{|100-UEATR|}$	0,010 0 %
Net supply airflow	Q_{SANET}	m³/s	0,064	← calculated value per Formulae (18) and (19)						

Formula (18)
Formula (19)

$$Q_{SANet} = \frac{NSAR}{100} \times Q_{SA} \;\; where \; NSAR = 100 - EATR$$

(rel)

$$\left(\frac{u(Q_{SA,Net})}{Q_{SA,Net}}\right)^2 = \left(\frac{u(UEATR)}{100-UEATR}\right)^2 + \left(\frac{u(Q_{SA})}{Q_{SA}}\right)^2$$

By uncertainty budget

Combined standard relative uncertainty $u(Y)/Y$	1,17 %
Expanded absolute uncertainty $U(Q)$	0,001 48
Expanded relative uncertainty $U(Y)/Y$	2,33 %

By formula at left

Combined standard relative uncertainty $u(Y)/Y$	1,17 %
Expanded relative uncertainty $U(Y)/Y$	2,33 %
For expanded uncertainty, coverage factor k = 2	

Table A.6 — Uncertainty budget sheet for net supply mass airflow $qm_{2,net}$

| Input quantity and/or source of uncertainty | Symbol | Units of measurement | Uncertainty of each Factor | | | | Value of standard uncertainty $u(x_i)$ | Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i \rvert}$ |
			Measured value	Expanded uncertainty	Probability distribution	Divisor		
Supply airflow	qm_2	kg/s	0,077 0	0,002 04	Normal	2	0,001 02	$\dfrac{u(qm_2)}{qm_2}$ 1,32 %
UEATR	$UEATR$	%	5,0	0,186	Normal	2	0,093	$\dfrac{u(UEATR)}{100-UEATR}$ 0,097 9
Net supply mass flow rate	**$qm_{2,net}$**	**kg/s**	**0,075 1**	←**calculated value per Formula (28)**				

Formula (28):

$$qm_{2,\text{net}} = qm_2\left(1 - \frac{UEATR}{100}\right)$$

(rel):

$$\left(\frac{u(qm_{2,\text{net}})}{qm_{2,\text{net}}}\right)^2 = \left(\frac{u(qm_2)}{qm_2}\right)^2 + \left(\frac{u(UEATR)}{100-UEATR}\right)^2$$

Combined standard relative uncertainty $u[Y]/Y$	By uncertainty budget	1,32 %
Expanded absolute uncertainty $U(Q)$		0,001 93
Expanded relative uncertainty $U(Y)/Y$		2,64 %
Combined standard relative uncertainty $u(Y)/Y$	By formula at left	2,68 %
Expanded relative uncertainty $U(Y)/Y$		5,36 %
For expanded uncertainty, coverage factor $k = 2$		

Table A.7 — Uncertainty budget sheet for power value of moving air P_{vma}

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Uncertainty of each factor				Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{|x_i|}$
			Measured value	Expanded uncertainty	Probability distribution	Divisor		
Static pressure at entering supply air (station 1)	ps_1	Pa	−20	2,5	Normal	2	1,250 0	$\dfrac{u(ps_n)}{\sum_{n=1}^{4}\left|ps_n + pv_n\right|}$
Static pressure at leaving supply air (station 2)	ps_2	Pa	30	2,5	Normal	2	1,250 0	
Static pressure at entering exhaust air (station 3)	ps_3	Pa	−20	2,5	Normal	2	1,250 0	
Static pressure at leaving exhaust air (station 4)	ps_4	Pa	30	2,5	Normal	2	1,250 0	
Velocity pressure at entering supply air (station 1)	pv_1	Pa	10	2,5	Normal	2	1,250 0	$\dfrac{u(pv_n)}{\sum_{n=1}^{4}\left|ps_n + pv_n\right|}$
Velocity pressure at leaving supply air (station 2)	pv_2	Pa	10	2,5	Normal	2	1,250 0	
Velocity pressure at entering exhaust air (station 3)	pv_3	Pa	10	2,5	Normal	2	1,250 0	
Velocity pressure at leaving exhaust air (station 4)	pv_4	Pa	10	2,5	Normal	2	1,250 0	

Relative standard uncertainty values: 1,25 % (all rows)

Table A.7 *(continued)*

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Measured value	Uncertainty of each factor			Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i \rvert}$	
				Expanded uncertainty	Probability distribution	Divisor			
The net supply mass flow rate at station 2	$qm_{2,\mathrm{net}}$	kg/s	0,075 1	0,001 0	Normal	2	0,000 5	$\dfrac{u(qm_{2,\mathrm{net}})}{qm_{2,\mathrm{net}}}$	0,67 %
Specific volume at leaving supply air (station 2)	v_{s}	m³/kg	0,820	0,010	Normal	2	0,005 0	$\dfrac{u(v_{\mathrm{s}})}{v_{\mathrm{s}}}$	0,61 %

Power value of moving Air	P_{vma}	J/s	12,320 1	← calculated value per Formula (29)

Formula (29)

$$P_{\mathrm{vma}} = \left(\sum_{n=1}^{4} \lvert ps_n + pv_n \rvert \right) 2qm_{2,\mathrm{net}}\, v_{\mathrm{s}}$$

(rel) Formula for relative uncertainty not provided because $u(P_{\mathrm{vma}})$ is used only in calculation of COE.

By uncertainty budget		
Combined standard relative uncertainty $u(Y)/Y$		3,65 %
Expanded absolute uncertainty $U(Q)$		0,899 0
Expanded relative uncertainty $U(Y)/Y$		7,30 %
For expanded uncertainty, coverage factor k = 2		

Table A.8 — Uncertainty budget sheet for gross effectiveness, sensible $\varepsilon_{\text{sensible}}$

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Measured value	Uncertainty of each factor			Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i \rvert}$
				Expanded uncertainty	Probability distribution	Divisor		
Dry-bulb temperature at entering supply air (station 1)	T_1	K	308,2	0,100 0	Normal	2	0,050 0	$1-\left\lvert\dfrac{\left(T_1-T_2-u(T_1)\right)\left(T_1-T_3\right)}{\left(T_1-T_3-u(T_1)\right)\left(T_1-T_2\right)}\right\rvert$ 0,21 %
Dry-bulb temperature at leaving supply air (station 2)	T_2	K	300,2	0,100 0	Normal	2	0,050 0	$\dfrac{u(T_2)}{\lvert T_1-T_2\rvert}$ 0,63 %
Dry-bulb temperature at entering exhaust air (station 3)	T_3	K	296,2	0,100 0	Normal	2	0,050 0	$1-\left\lvert\dfrac{\left(T_1-T_3\right)}{T_1-T_3-u(T_3)}\right\rvert$ 0,42 %
Gross effectiveness, sensible	e_{sensible}	%	0,667	← calculated value per Formula (25)				

$$\varepsilon_{\text{sensible}} = \frac{T_1-T_2}{T_1-T_3}$$

Formula (25)[a]

(rel)

$$\left(\frac{u(\varepsilon_{\text{sensible}})}{\varepsilon_{\text{sensible}}}\right)^2 = \left(1-\frac{\left(T_1-T_2-u(T_1)\right)\left(T_1-T_3\right)}{\left(T_1-T_3-u(T_1)\right)\left(T_1-T_2\right)}\right)^2 +$$

$$\left(\frac{u(T_2)}{T_1-T_2}\right)^2 + \left(1-\frac{\left(T_1-T_3\right)}{\left(T_1-T_3-u(T_3)\right)}\right)^2$$

By uncertainty budget	Combined standard relative uncertainty $u(Y)/Y$ 0,78 %
	Expanded absolute uncertainty $U(Q)$ 0,010 4
	Expanded relative uncertainty $U(Y)/Y$ 1,56 %
By formula at left	Combined standard relative uncertainty $u(Y)/Y$ 0,78 %
	Expanded relative uncertainty $U(Y)/Y$ 1,56 %
	For expanded uncertainty, coverage factor $k = 2$

[a] "T" is substituted here for "x" to indicate these calculations are for sensible effectiveness.

Table A.9 — Uncertainty budget sheet for gross effectiveness, latent ε_{latent}

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Uncertainty of each factor				Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{|x_i|}$
			Measured value	Expanded uncertainty	Probability distribution	Divisor		
Absolute humidity ratio at entering supply air (station 1)	W_1	kg_w / kg_{da}	0,017 9	0,000 1	Normal	2	0,000 05	$1 - \left\| \dfrac{(W_1 - W_2 - u(W_1))(W_1 - W_3)}{(W_1 - W_3 - u(W_1))(W_1 - W_2)} \right\|$ 0,40 %
Absolute humidity ratio at leaving supply air (station 2)	W_2	kg_w / kg_{da}	0,013 0	0,000 1	Normal	2	0,000 05	$\dfrac{u(W_2)}{|W_1 - W_2|}$ 1,02 %
Absolute humidity ratio at entering exhaust air (station 3)	W_3	kg_w / kg_{da}	0,009 9	0,000 1	Normal	2	0,000 05	$1 - \left\| \dfrac{(W_1 - W_3)}{(W_1 - W_3 - u(W_3))} \right\|$ 0,63 %

Gross effectiveness, latent	e_{latent}	%	0,613	← calculated value per Formula (25)

Formula (25)[a]

$$\varepsilon_{latent} = \dfrac{W_1 - W_2}{W_1 - W_3}$$

(rel)

$$\left(\dfrac{u(\varepsilon_{latent})}{\varepsilon_{latent}} \right)^2 = \left(1 - \dfrac{(W_1 - W_2 - u(W_1))(W_1 - W_3)}{(W_1 - W_3 - u(W_1))(W_1 - W_2)} \right)^2 + \left(\dfrac{u(W_2)}{W_1 - W_2} \right)^2 + \left(1 - \dfrac{(W_1 - W_3)}{(W_1 - W_3 - u(W_3))} \right)^2$$

By uncertainty budget	Combined standard relative uncertainty $u(Y)/Y$	1,26 %
	Expanded absolute uncertainty $U(Q)$	0,015 5
	Expanded relative uncertainty $U(Y)/Y$	2,53 %
By formula at left	Combined standard relative uncertainty $u(Y)/Y$	1,26 %
	Expanded relative uncertainty $U(Y)/Y$	2,53 %
	For expanded uncertainty, coverage factor $k = 2$	

[a] "W" is substituted here for "x" to indicate these calculations are for latent effectiveness.

Table A.10 — Uncertainty budget sheet for gross effectiveness, total ε_{total}

Input quantity and/or source of uncertainty	Symbol	Units of measure-ment	Uncertainty of each factor				Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i \rvert}$
			Measured value	Expanded uncertainty	Probability distribution	Divisor		
Enthalpy at entering supply air (station 1)	h_1	kJ/kg$_{da}$	81,100 0	0,250 0	Normal	2	0,125 0	$1 - \left\lvert \dfrac{(h_1-h_2-u(h_1))(h_1-h_3)}{(h_1-h_3-u(h_1))(h_1-h_2)} \right\rvert$ 0,30 %
Enthalpy at leaving supply air (station 2)	h_2	kJ/kg$_{da}$	62,600 0	0,250 0	Normal	2	0,125 0	$\dfrac{u(h_2)}{\lvert h_1-h_2 \rvert}$ 0,68 %
Enthalpy at entering exhaust air (station 3)	h_3	kJ/kg$_{da}$	48,300 0	0,250 0	Normal	2	0,125 0	$1 - \left\lvert \dfrac{(h_1-h_3)}{(h_1-h_3-u(h_3))} \right\rvert$ 0,38 %
Gross effectiveness, total	e_{total}	%	0,564 0 $\leftarrow$ calculated value per Formula (25)					

Formula (25) [a]

$$\varepsilon_{total} = \frac{h_1 - h_2}{h_1 - h_3}$$

(rel)

$$\left(\frac{u(\varepsilon_{total})}{\varepsilon_{total}}\right)^2 = \left(1 - \frac{(h_1-h_2-u(h_1))(h_1-h_3)}{(h_1-h_3-u(h_1))(h_1-h_2)}\right)^2 +$$

$$\left(\frac{u(h_2)}{h_1-h_2}\right)^2 + \left(1 - \frac{(h_1-h_3)}{(h_1-h_3-u(h_3))}\right)^2$$

	By uncertainty budget	By formula at left
Combined standard relative uncertainty $u(Y)/Y$	0,83 %	
Expanded absolute uncertainty $U(Q)$	0,009 4	
Expanded relative uncertainty $U(Y)/Y$	1,66 %	
Combined standard relative uncertainty $u(Y)/Y$		0,83 %
Expanded relative uncertainty $U(Y)/Y$		1,66 %
		For expanded uncertainty, coverage factor $k = 2$

[a] "h" is substituted here for "x" to indicate these calculations are for total effectiveness.

Table A.11 — Uncertainty budget sheet for coefficient of energy, ducted ventilator, total COE_{ducted}

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Measured value	Uncertainty of each factor			Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i \rvert}$
				Expanded uncertainty	Probability distribution	Divisor		
Net supply airflow rate	$qm_{2,net}$	kg/s	0,075 1	0,001 0	Normal	2	0,000 5	$\dfrac{u(qm_{2,net})\lvert h_2-h_1\rvert 1\,000}{qm_{2,net}\lvert h_2-h_1\rvert 1\,000 + P_{vma}}$ 0,69 %
Enthalpy at leaving supply air (station 2)	h_2	kJ/kg of dry air	81,100 0	0,250 0	Normal	2	0,125 0	$\dfrac{qm_{2,net}\,u(h_1)\,1\,000}{qm_{2,net}\lvert h_2-h_1\rvert 1\,000 + P_{vma}}$ 0,67 %
Enthalpy at entering supply air (station 1)	h_1	kJ/kg of dry air	62,600 0	0,250 0	Normal	2	0,125 0	$\dfrac{qm_{2,net}\,u(h_2)\,1\,000}{qm_{2,net}\lvert h_2-h_1\rvert 1\,000 + P_{vma}}$ 0,67 %
Power value of moving air	P_{vma}	(W)	12,316 4	0,073 0	Normal	2	0,036 5	$\dfrac{u(P_{vma})}{qm_{2,net}\lvert h_2-h_1\rvert 1\,000 + P_{vma}}$ 0,003 %
Power input to unit	P_{in}	W	110,000 0	1,10	Normal	2	0,550 0	$\dfrac{u(P_{in})\,P_{in}}{P_{in}^{\,2}-u(P_{in})\,P_{in}}$ 0,50 %
Coefficient of energy, total, ducted	**COE**	**W/W**	**12,746 2**	← calculated value per Formula (27)				

By uncertainty budget:

Combined standard relative uncertainty $u(Y)/Y$	1,28 %
Expanded absolute uncertainty $U(Q)$	0,325 3
Expanded relative uncertainty $U(Y)/Y$	2,55 %

Formula (27)

$$COE_{DUCTED} = \frac{\left(\lvert qm_{2,net}\,(h_2-h_1)\rvert \times 1\,000\right) + P_{vma}}{P_{in}}$$

Table A.11 *(continued)*

		Combined standard relative uncertainty $u(Y)/Y$	1,28 %
		Expanded relative uncertainty $U(Y)/Y$	2,55 %
[rel]	$$\left(\frac{U(COE_{\text{ducted}})}{COE_{\text{ducted}}}\right)^2 = \left(\frac{u(qm_{2,\text{net}})|h_2-h_1|1\,000}{qm_{2,\text{net}}|h_2-h_1|1\,000+P_{\text{vma}}}\right)^2 + \left(\frac{qm_{2,\text{net}}\,u(h_2)\,1\,000}{qm_{2,\text{net}}|h_2-h_1|1\,000+P_{\text{vma}}}\right)^2 + $$ $$\left(\frac{qm_{2,\text{net}}\,u(h_1)\,1\,000}{qm_{2,\text{net}}|h_2-h_1|1\,000+P_{\text{vma}}}\right)^2 + \left(\frac{u(P_{\text{vma}})}{qm_{2,\text{net}}|h_2-h_1|1\,000+P_{\text{vma}}}\right)^2 + \left(\frac{u(P_{\text{in}})P_{\text{in}}}{P_{\text{in}}^2-u(P_{\text{in}})P_{\text{in}}}\right)^2$$	By formula at left	*For expanded uncertainty, coverage factor k = 2*

Table A.12 — Uncertainty budget for coefficient of energy, ducted ventilator, sensible $COE_{ducted,sensible}$

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Measured value	Uncertainty of each factor			Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{\lvert x_i\rvert}$
				Expanded uncertainty	Probability distribution	Divisor		
Net supply airflow rate	$qm_{2,net}$	kg/s	0,075 1	0,001 0	Normal	2	0,000 5	$\dfrac{u(qm_{2,net})C_p(T_2-T_1)\times1000}{qm_{2,net}(T_2-T_1)\times1000+P_{vma}}$ — 0,68 %
Specific heat of air	C_p	kJ/kgK	1,005	0,001 0	Normal	2	0,000 5	$\dfrac{qm_{2,net}\,u(C_p)(T_2-T_1)\times1000}{qm_{2,net}C_p(T_2-T_1)\times1000+P_{vma}}$ — 0,05 %
Drybulb temperature at entering supply air (station 1)	T_1	K	300,200 0	0,100 0	Normal	2	0,050 0	$\dfrac{qm_{2,net}\,u(T)1000}{\left\lvert qm_{2,net}C_p(T_2-T_1)\times1000+P_{vma}\right\rvert}$ — 0,61 %
Drybulb temperature at leaving supply air (station 2)	T_2	K	308,200 0	0,100 0	Normal	2	0,050 0	$\dfrac{qm_{2,net}\,u(T_1)1000}{\left\lvert qm_{2,net}C_p(T_2-T_1)\times1000+P_{vma}\right\rvert}$ — 0,61 %
Power value of moving air	P_{vma}	W	12,316 4	0,073 0	Normal	2	0,036 5	$\dfrac{u(P_{vma})}{\left\lvert qm_{2,net}C_p(T_2-T_1)\times1000+P_{vma}\right\rvert}$ — 0,01 %
Power input to unit	P_{in}	W	110,	1,100 0	Normal	2	0,550 0	$\dfrac{u(P_{in})P_{in}}{P_{in}^2-u(P_{in})P_{in}}$ — 0,50 %
Coefficient of energy, ducted, sensible	$COE_{ducted,sensible}$	W/W	5,602 7	← calculated value per Formula (27)				

Formula (27)[a]

$$COE_{DUCTED,sensible}=\frac{\left(\left\lvert qm_{2,net}\,C_p(T_2-T_1)\right\rvert\times1000\right)+P_{vma}}{P_{in}}$$

By Uncertainty Budget	
Combined standard relative uncertainty $u(Y)/Y$	1,21 %
Expanded absolute uncertainty $U(Q)$	0,135 7
Expanded relative uncertainty $U(Y)/Y$	2,42 %

[a] "$C_p(T_2-T_1)$" is substituted here for "(h_2-h_1)" to provide calculations for sensible effectiveness.

Table A.12 *(continued)*

| | | Combined standard relative uncertainty $u(Y)/Y$ | 1,21 % |
| | | Expanded relative uncertainty $U(Y)/Y$ | 2,42 % |

For expanded uncertainty, coverage factor k = 2

(rel)

By formula at left

$$\left(\frac{u\left(COE_{\text{ducted,sensible}}\right)}{COE_{\text{ducted,sensible}}}\right)^2$$

$$= \left(\frac{u\left(qm_{2,\text{net}}\right)C_{\text{p}}\left(T_2-T_1\right)\times1\,000}{qm_{2,\text{net}}\left(T_2-T_1\right)\times1\,000+P_{\text{vma}}}\right)^2 + \left(\frac{qm_{2,\text{net}}\,u\left(T_1\right)1\,000}{qm_{2,\text{net}}\,C_{\text{p}}\left(T_2-T_1\right)\times1\,000+P_{\text{vma}}}\right)^2 +$$

$$\left(\frac{qm_{2,\text{net}}\,u\left(T\right)1\,000}{qm_{2,\text{net}}\,C_{\text{p}}\left(T_2-T_1\right)\times1\,000+P_{\text{vma}}}\right)^2 +$$

$$\left(\frac{u\left(P_{\text{vma}}\right)}{qm_{2,\text{net}}\,C_{\text{p}}\left(T_2-T_1\right)\times1\,000+P_{\text{vma}}}\right)^2 +$$

$$\left(\frac{u\left(P_{\text{in}}\right)P_{\text{in}}}{P_{\text{in}}^{\,2}-u\left(P_{\text{in}}\right)P_{\text{in}}}\right)^2 + \left(\frac{qm_{2,\text{net}}\,u\left(C_{\text{p}}\right)\left(T_2-T_1\right)\times1\,000}{qm_{2,\text{net}}\,C_{\text{p}}\left(T_2-T_1\right)\times1\,000+P_{\text{vma}}}\right)^2$$

a   "$C_{\text{p}}(T_2-T_1)$" is substituted here for "(h_2-h_1)" to provide calculations for sensible effectiveness.

Table A.13 — Uncertainty budget sheet for coefficient of energy, total, unducted ventilator COE_{unducted}

Input quantity and/or source of uncertainty	Symbol	Units of measurement	Uncertainty of each factor				Value of standard uncertainty $u(x_i)$	Relative standard uncertainty of each value $\dfrac{p_i u(x_i)}{|x_i|}$	
			Measured value	Expanded uncertainty	Probability distribution	Divisor			
Net supply airflow rate	$qm_{2,\text{net}}$	kg/s	0,075 1	0,004 4	Normal	2	0,000 5	$=\dfrac{u(qm_{2,\text{net}})|h_2-h_1|1000}{qm_{2,\text{net}}|h_2-h_1|1000}$	0,70 %
Enthalpy at leaving supply air (station 2)	h_2	kJ/kg$_{\text{da}}$	81,1	1,622	Normal	2	0,125 0	$=\dfrac{qm_{2,\text{net}}u(h_1)1000}{qm_{2,\text{net}}|h_2-h_1|1000}$	0,68 %
Enthalpy at entering supply air (station 1)	h_1	kJ/kg$_{\text{da}}$	62,6	1,252	Normal	2	0,125 0	$=\dfrac{qm_{2,\text{net}}u(h_2)1000}{qm_{2,\text{net}}|h_2-h_1|1000}$	0,68 %
Power input to unit	P_{in}	W	110	1,10	Normal	2	0,550 0	$=\dfrac{u(P_{\text{in}})P_{\text{in}}}{P_{\text{in}}^{\,2}-u(P_{\text{in}})P_{\text{in}}}$	0,50 %
Coefficient of energy, unducted, total	COE	W/W	12,634 2 ← calculated value per Formula (36)						

	Combined standard relative uncertainty $u(Y)/Y$	1,29 %
By uncertainty budget	Expanded absolute uncertainty $U(Q)$	0,324 8
	Expanded relative uncertainty $U(Y)/Y$	2,58 %
By formula at left	Combined standard relative uncertainty $u(Y)/Y$	1,29 %
	Expanded relative uncertainty $U(Y)/Y$	2,58 %

For expanded uncertainty, coverage factor k = 2

Formula (36)

$$COE_{\text{unducted}} = \frac{\left(|qm_{2,\text{net}}\,(h_2-h_1)|\times 1000\right)}{P_{\text{in}}}$$

(rel)

$$\left(\frac{U(COE_{\text{unducted}})}{COE_{\text{unducted}}}\right)^2 = \left(\frac{u(qm_{2,\text{net}})|h_2-h_1|1000}{qm_{2,\text{net}}|h_2-h_1|1000}\right)^2 +$$

$$\left(\frac{qm_{2,\text{net}}u(h_1)1000}{qm_{2,\text{net}}|h_2-h_1|1000}\right)^2 + \left(\frac{qm_{2,\text{net}}u(h_2)1000}{qm_{2,\text{net}}|h_2-h_1|1000}\right)^2 + \left(\frac{u(P_{\text{in}})P_{\text{in}}}{P_{\text{in}}^{\,2}-u(P_{\text{in}})P_{\text{in}}}\right)^2$$