Valeriy DESHKO
Irina SUKHODUB
Nguen Van PHUC

National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"

DETERMINATION OF SHORTCUTS IN VENTILATION UNITS WITH ENERGY RECOVERY

Introduction

The need to organize air exchange by means of mechanical ventilation is a crucial issue in air-tight buildings, especially in terms of air quality. The use of supply and exhaust ventilation system with heat recovery allows to reduce the cost of supply air heating and cooling. Plate recuperative heat exchangers are often used in small decentralized ventilation systems, having a sufficiently high efficiency. However, unintended air flows inside the unit may lead to a decrease in both the quality of supply air, and recovery effectiveness. The most popular methods for air leakages and shortcuts determination are pressure and tracer gas techniques. Analysis of air flow in ventilation systems with heat recovery can be performed using the method of measuring tracer gas concentration in certain points of the air-handling unit (AHU) [1, 2]. Theoretical and experimental study of such systems can be found inreference [3]. You can also find results of field study of volume flow unbalances and shortcuts in centralized and decentralized ventilation system [4, 5]. Internal shortcuts definition in AHU with plate heat exchangers was conducted using measurements of mass air flow rate in supply and exhaust channels, air inlet and outlet temperatures in heat exchanger and unit and appropriate air energy and mass balances [6, 7].

Objects and methods

The main objective of this paper is to study the impact of temperatures and mass flow rates measurement errors on heat flow value, internal shortcuts and the unbalances in AHU. To achieve this goal the following studies have been conducted:

- experimental studies are conducted to determine the temperature, mass flow rates and pressure at specific points in the AHU; the internal flows in the system for winter and summer operation conditions are defined based on the mathematical model [6, 7];
- knowing the values of mass flows rates and inlet and outlet air temperatures in heat exchanger and unit, a model is developed to calculate the values of shortcuts for AHU and mass flow rates depending on the temperature and mass flow rate measuring errors;
- the total error of recovered heat flow, shortcuts and energy imbalance (for heat exchanger and AHU) is calculated and analyzed by varying the temperature and mass flow rate measurements errors.

Commercial ventilation system with membrane heat exchanger was studied in previous papers [6, 7]. Laboratory equipped with supply and exhaust ventilation unit was chosen as the object of study. Volume flow rate in supply and exhaust channels varies between 70-150 m^3/h depending on fans mode and diffusers position. Experimental unit also includes air ductworks, filters, diffusers, louvers and air properties measurement sleeves. Experimental unit construction scheme can be found in reference [7]. During the experimental studies researchers are often faced with the non-completion of AHU heat and mass balances. Therefore, the assumption of the nonregistered flows in unit is allowed.

If it is not possible to carry out the experiment using tracer gas technique, such a research can be carried out on the basis of mass flow and energy balances. Figure 1 shows the designation of mass flow rates and air temperatures at different points of AHU.

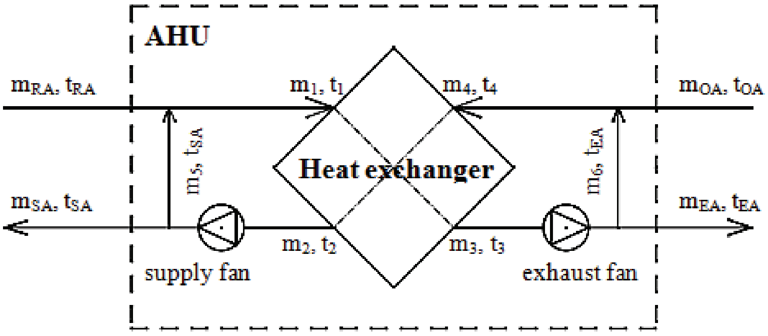

FIGURE 1. *Mass flow rates and temperature in AHU: RA – return air, OA – outside air, SA – supply air, EA – exhaust air, m – mass flow rate, kg/s, t – temperature, ℃*

Temperatures in different points of AHU were measured by Hygrochron DS 1923-F5 with data storage possibility. Volume air flow rates were measured by hot-wire air flow meter Testo-405. To test the temperature and humidity measurement accuracy obtained data were compared with measurements from thermal hygrometer Testo-605 and thermocouples.

Two internal air flows, which reduce AHU performance, were considered. The first flow is m_5, where a part of the supply air is mixed with the exhaust air and then enters the heat exchanger. The second flow is m_6, where a part of the exhaust air is mixed with the outside air and then enters the heat exchanger (Fig. 1). Also, the temperature of the supply and exhaust air is influenced by heating in fans.

Determining the pressure difference between the nodes

As it is known, the direction of the internal flows in ventilation systems depends on fan positions in the supply and exhaust air channels. Pressure at the points *SA*, *RA*, *OA*, *EA* was measured to confirm the direction of flows m_5 and m_6. The measurements were performed by VelociCalc Plus Multi-Parameter Meter (pressure measurement accuracy ±1 Pa). Fan speed and supply and exhaust diffusers position were changed during the study. Measurement results for overpressure and vacuum pressure are shown in Tables 1 and 2. The pressure values at these points confirm the direction of possible flows. The pressure difference between the nodes *SA&RA* is $\Delta P_5 = P_{SA} - P_{RA}$. The pressure difference between the nodes *OA&EA* is $\Delta P_6 = P_{EA} - P_{OA}$.

TABLE 1. *Experiment results for high fan speed*

Diffuser positions	Closed	Partly pen	Fully open
P_{SA}, kPa	0.068	0.045	0.05
P_{RA}, kPa	-0.103	-0.093	-0.042
ΔP_5, kPa	0.175	0.137	0.089
P_{OA}, kPa	-0.077	-0.086	-0.07
P_{EA}, kPa	0.042	0.042	0.058
ΔP_6, kPa	0.122	0.126	0.127

TABLE 2. *Experiment results forlow fan speed*

Diffuser positions	Closed	Partly open	Fully open
P_{SA}, kPa	0.034	0.02	0.026
P_{RA}, kPa	-0.078	-0.039	-0.029
ΔP_5, kPa	0.11	0.059	0.052
P_{OA}, kPa	-0.06	-0.054	-0.047
P_{EA}, kPa	0.035	0.045	0.048
ΔP_6, kPa	0.094	0.097	0.094

Pressure differences ΔP_5 and ΔP_6 are also shown graphically in Figure 2.

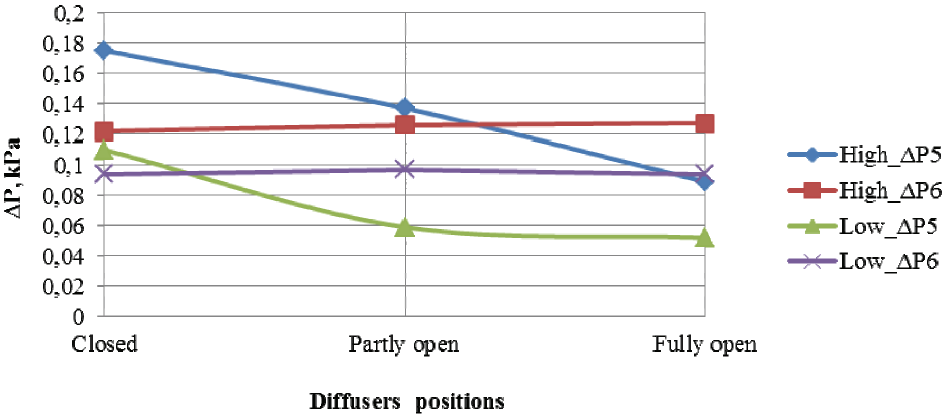

FIGURE 2. *Pressure difference at the nodes*

From the above results, we can see there's always the pressure difference between the nodes *SA&RA* ($\Delta P_5 \neq 0$) and between *EA&OA* ($\Delta P_6 \neq 0$). For this reason two air flows m_5 and m_6 also always exist. On the other hand, these values are dependent on the fan speed and diffusers position.

The method for determining mass flows and temperature on the basis of energy and material balances. Using previously obtained results of experimental studies on the mass flow rate (m_{EA}, m_{SA}), coefficients of internal shortcuts (εint_1 and εint_2) and efficiency of heat exchanger (l_t) and fan (l_{fan}), as well as changing the temperature of the supply and exhaust air at the entrance to the AHU (t_{RA}, t_{OA}), mathematical model was created to calculate the missing temperatures and air flows (t_1, t_2, t_3, t_4, t_{SA}, t_{EA}, m_1, m_2, m_3, m_4, m_5, m_6, m_{OA}, m_{RA}):

$$m_1 = m_3 \tag{1}$$

$$m_2 = m_4 \tag{2}$$

$$m_1 = m_5 + m_{RA} \tag{3}$$

$$m_4 = m_6 + m_{OA} \tag{4}$$

$$m_2 = m_5 + m_{SA} \tag{5}$$

$$m_3 = m_6 + m_{EA} \tag{6}$$

$$m_1 c_P t_1 = m_5 c_P t_{SA} + m_{RA} c_P t_{RA} \tag{7}$$

$$m_4 c_P t_4 = m_6 c_P t_{EA} + m_{OA} c_P t_{OA} \tag{8}$$

$$\eta_t = \frac{m_1 c_P (t_3 - t_1)}{m_{\min} c_P (t_4 - t_1)} \tag{9}$$

$$\eta_t = \frac{m_2 c_P (t_4 - t_2)}{m_{\min} c_P (t_4 - t_1)} \tag{10}$$

$$t_{SA} = t_2 + \frac{N(1 - \eta_{fan})}{2 c_P m_2} \tag{11}$$

$$t_{EA} = t_3 + \frac{N(1 - \eta_{fan})}{2 c_P m_3} \tag{12}$$

$$\varepsilon \mathrm{int}_1 = \frac{m_5}{m_1} \tag{13}$$

$$\varepsilon \mathrm{int}_2 = \frac{m_6}{m_2} \tag{14}$$

where: c_P – specific heat capacity; N – the total electric power of fan motors.

Sensible recovered heat flow in the heat exchanger is calculated as follows:

$$Q_1 = m_1 c_P \left(t_1 - t_3\right) \tag{15}$$

$$Q_2 = m_2 c_P \left(t_2 - t_4\right) \tag{16}$$

Example of input data and calculation results are shown in Tables 3 and 4. Energy imbalance for heat exchanger and for AHU in this case is zero.

Table 3. *Input data*

t_{RA}, °C	t_{OA}, °C	m_{EA}, kg/s	m_{SA}, kg/s	εint$_1$	εint$_2$	l_t	l_v
15	35	0.05	0.05	0.1	0.3	0.793	0.6

TABLE 4. *Calculations results*

t_1, °C	t_2, °C	t_3, °C	t_4, °C	t_{SA}, °C	t_{EA}, °C	m_1, kg/s	m_2, kg/s	m_3, kg/s	m_4, kg/s	m_5, kg/s	m_6, kg/s	m_{OA}, kg/s	m_{RA}, kg/s
15.4	19.0	27.0	32.7	19.3	27.2	0.067	0.057	0.067	0.057	0.0067	0.017	0.040	0.060

This method is used to calculate mass flow rates and temperatures for different t_{RA} and t_{OA}, mass flow rates, coefficients of internal shortcuts as basic data for the study of temperature uncertainty effect on shortcuts determination method.

Total inaccuracy estimation of recovered heat flows and mass flow rates. Mathematical model based on formulas (1)-(8) was used incorporating temperature and mass flow measurement errors to determine the total relative error of heat flows and internal shortcuts coefficients.

It was found that values of the heat flow and the coefficients of internal shortcuts are the function of temperature mass airflow rates variations. For that reason their total inaccuracy depends on these variables:

$$\sigma\left(y_i\right) = \sqrt{\sum_{j=1}^{n} \left(\frac{\partial y_i}{\partial x_j} \frac{\Delta x_j}{y_i} \right)^2} = \sqrt{\sum_{j=1}^{n} \left[\sigma\left(y_i(x_j) \right) \right]^2} \tag{17}$$

where: $y_i = \left\{ Q_1, Q_2, \varepsilon \mathrm{int}_1, \varepsilon \mathrm{int}_2 \right\}$; $x_j = \left\{ t_1, t_2, t_3, t_4, t_{RA}, t_{OA}, t_{EA}, t_{SA}, m_{EA}, m_{SA} \right\}$; σ – the relative error of indirect measurement; Δ – the total absolute error of direct measurement.

Uncertainty of energy balance in the heat exchanger is calculated as follows:

$$\delta Q \Sigma_{HE} = \sqrt{\sum_{j=1}^{n} (\delta Q_{HE}(x_j))^2} \tag{18}$$

$$\delta Q_{HE} = \frac{\left| Q_2 - Q_1 \right|}{\left(Q_2 + Q_1\right)/2} \tag{19}$$

Uncertainty of energy balance for AHU is calculated as follows:

$$\delta Q\Sigma_{AHU} = \sqrt{\sum_{j=1}^{n} \left(\delta Q_{AHU}(x_j)\right)^2} \tag{20}$$

$$\delta Q_{AHU} = \frac{\left| m_{RA} c_P t_{RA} + m_{OA} c_P t_{OA} + N(1-\eta_V) - (m_{SA} c_P t_{SA} + m_{EA} c_P t_{EA}) \right|}{m_{RA} c_P (t_{OA} - t_{RA})} \tag{21}$$

Let the initial data for calculation be the following: $\varepsilon int_1 = 0.1$, $\varepsilon int_2 = 0.3$, $\Delta t = t_{OA} - t_{RA} = 20°C$, $\Delta = 0.2°C$. Accuracy of mass flow measurement is assumed constant and equal to 5%. The calculation results for relative errors and balances uncertainty are shown in Table 5.

TABLE 5. *The results of calculations for errors components*

	t_1	t_2	t_3	t_4	t_{RA}	t_{OA}	t_{EA}	t_{SA}	m_{EA}	m_{SA}
σQ_1	0.003	0	0.017	0.022	0.013	0.016	0.007	0.001	0.077	0.023
σQ_2	0.057	0.015	0	0.022	0.051	0.002	0.001	0.006	0.009	0.091
$\sigma \varepsilon int_1$	0.4679	0	0	0	0.421	0	0	0.047	0	0
$\sigma \varepsilon int_2$	0	0	0	0.086	0	0.060	0.026	0	0	0
δQ_{HE}	0.060	0.015	0.017	0.034	0.039	0.014	0.006	0.004	0.034	0.034
δQ_{AHU}	0.038	0	0	0.023	0.024	0.009	0.015	0.012	0.022	0.021

Notably, when the shortcut m_5 proportion is relatively small its errors components for t_{RA} and t_1 have relatively great value, but it does not have much impact on the error of thermal characteristics determination.

The total measurement errors are determined by formulas (17), (18), (20). The calculation results are shown in Table 6.

TABLE 6. *The results of total errors and uncertainties calculations*

$\sigma Q_{1\Sigma}$	$\sigma Q_{2\Sigma}$	$\sigma \varepsilon int_{1\Sigma}$	$\sigma \varepsilon int_{2\Sigma}$	$\delta Q_{HE\Sigma}$	$\delta Q_{AHU\Sigma}$
0.088	0.121	0.631	0.108	0.097	0.062

Based on the above method, it is possible to identify measurements errors in other cases such as: $\varepsilon int_1 = 0.1$, $\varepsilon int_2 = 0.3$, $\Delta t = t_{OA} - t_{RA} = \{10,15,20,25\}°C$; $\Delta = \{0.1, 0.2, 0.3, 0.4, 0.5\}°C$. Total errors and uncertainties of the indirect measurements are shown on the Figure 3.

Total errors and uncertainties values are inversely proportional to those of the temperature difference between outdoor and indoor air. Also, the error values and uncertainties are directly proportional to the temperature measurement accuracy.

Results of total errors values for other coefficients of internal shortcuts are shown in Table 7 ($\Delta t = t_{OA} - t_{RA} = 20°C$, $\Delta = 0.2°C$). Analyzing the data from Table 7 it can be seen that the values of total errors and uncertainties strongly depend on the coefficients of internal shortcuts, especially in the case when $\varepsilon int_1 = 0.3$, $\varepsilon int_2 = 0.1$.

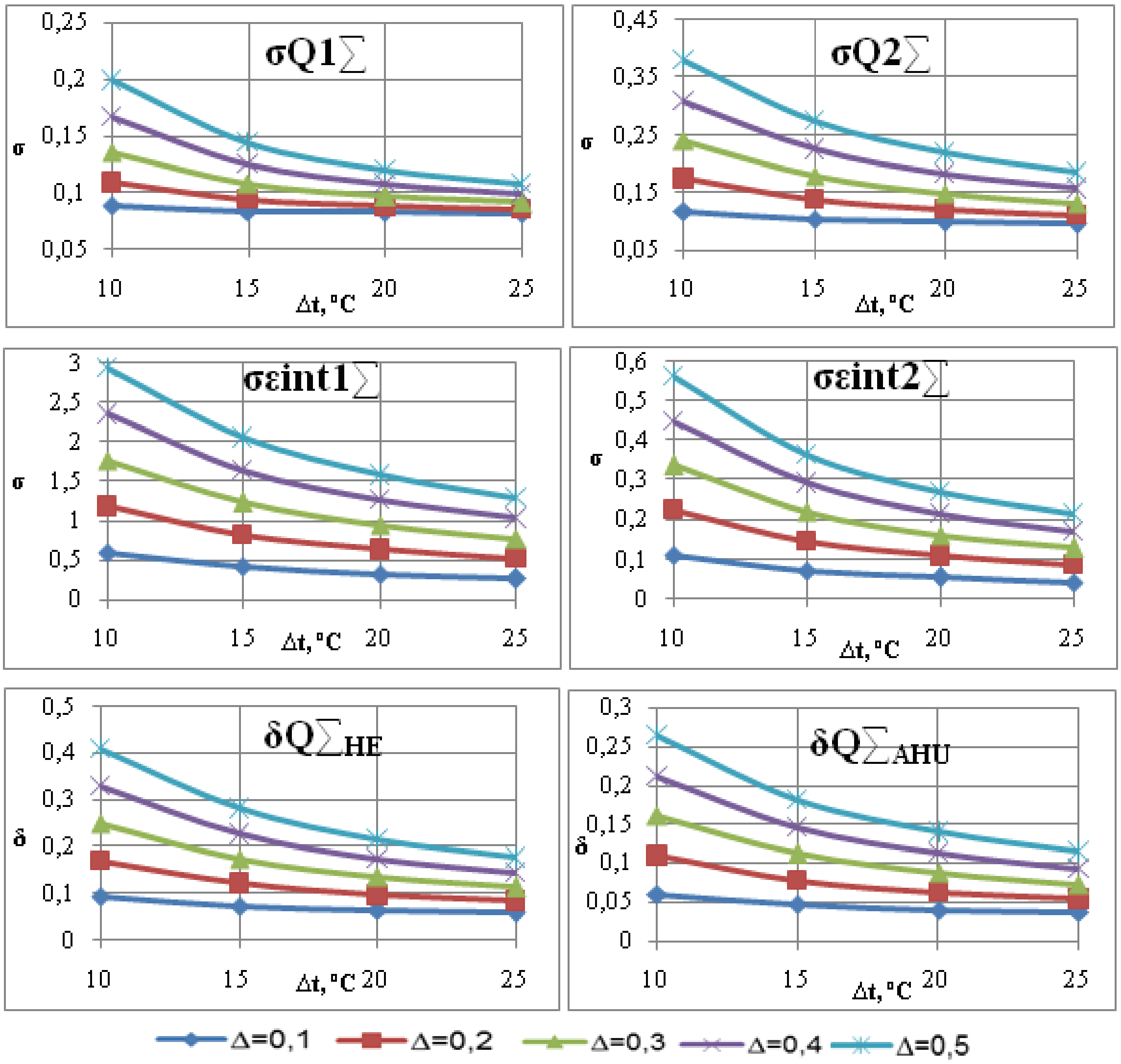

FIGURE 3. Total errors for recovered heat flow, internal shortcuts coefficients and energy balances uncertainties in heat exchanger and AHU

TABLE 7. The results of calculations

Shortcuts	$\delta Q_1\sum$	$\delta Q_2\sum$	$\delta\varepsilon int_1\sum$	$\delta\varepsilon int_2\sum$	$\delta Q\sum$	$\delta Q_z\sum$
$\varepsilon int_1 = 0.1$ $\varepsilon int_2 = 0.1$	0.114	0.109	0.573	0.661	0.112	0.095
$\varepsilon int_1 = 0.1$ $\varepsilon int_2 = 0.3$	0.088	0.121	0.631	0.108	0.097	0.062
$\varepsilon int_1 = 0.3$ $\varepsilon int_2 = 0.1$	0.355	0.119	0.147	2.812	0.268	0.342
$\varepsilon int_1 = 0.3$ $\varepsilon int_2 = 0.3$	0.101	0.097	0.157	0.178	0.085	0.085

Conclusions

The results demonstrate that the accuracy of the method for determining unintended air flows in ventilation systems with heat recovery from the measurement of temperature and mass flow rates is largely dependent on the measurement accuracy, and the temperature difference between supply and exhaust air at the entrance to the AHU. The value and location of the shortcuts themselves have a significant impact on the total error of their determination, and the error in the determination of the recovered heat flow and energy balance uncertainty for heat exchanger and AHU. The proposed method and the results allow selecting experimental conditions, especially temperature difference, in order to provide the desired accuracy and reliability in internal shortcuts determination.

References

[1] Manz H., *Performance of single room ventilation units with recuperative or regenerative heat recovery* / H. Manz, H. Huber, A. Schälin, A. Weber, M. Ferrazzini, M. Studer, Energy and Buildings, 2000, No 32, pp. 37-47.

[2] Manz H., *Impact of air leakages and short circuits in ventilation units with heat recovery on ventilation efficiency and energy requirements for heating* / H. Manz, H. Huber, D. Helfenfinger, Energy and buildings, 2001, No 33, pp. 133-139.

[3] Roulet C.-A., *Real heat recovery with air handling units* / C.-A. Roulet, F.D. Heidt, F. Foradini, M.-C. Pibiri, Energy and buildings, 2001, No 33, pp. 495-502.

[4] Merzkirch A., *Field tests of centralized and decentralized ventilation units in residential buildings – specific fan power, heat recovery efficiency, shortcuts and volume flow unbalances* / A. Merzkirch, S. Maas, F. Scholzen, D. Waldmann, Energy and buildings, in press.

[5] Merzkirch A., *Volume flow unbalances and shortcuts in decentralized and centralized ventilation units – field tests in residential buildings* / A. Merzkirch, S. Maas, F. Scholzen, D. Waldmann, 45th KGH HVAC&R conference, Belgrad, 2014, http://hdl.handle.net/10993/22936.

[6] Deshko V.I., *The efficiency of heat recovery in recuperative heat exchangers of ventilation systems* / V.I. Deshko, I.O. Sukhodub, S.O. Nagorna, Energy and Electrification, 2010, No 12, pp. 37-43.

[7] Deshko V.I., *Energy balance of ventilation system with energy recovery* / V.I. Deshko, I.O. Sukhodub, A.V. Popkov, Building constructions, 2014, No 77, pp. 213-216.