- Detailed Professional Report -

In the first year of the OTKA PD research programme the necessary devices of the test facility was purchased: the regenerative energy recovery, 2 variable speed fans with variable frequency drives, control system to control the speed of the supply and exhaust fans and the rotary of the energy recovery, air ducts and fittings, chiller. The test facility was installed into the Macskasy Indoor Air Quality and Thermal Comfort Laboratory at the Department of Building Services Engineering and Process Engineering. In the first year extensive scientific literature studies and theoretical research in the topic was achieved. From the results of the research work totally two pieces of international peer-reviewed scientific journal papers (from which one has high impact factor) and three pieces of international conference papers were published during the first year [1-5].

During the second year of the research, the sensible, latent and total effectiveness values were investigated by experimental tests extending the data given by the producer providing extended operating temperature and humidity ranges [6-11]. In the course of designing the measurement stand, the primary objective was to develop a measurement device, which is capable of establishing and permanently maintaining extreme outdoor states of air. Cooling or heating of supply air was provided by a direct evaporation type plate heat exchanger, as an ambient air temperature generator, supplied with a coolant of appropriate temperature by the heat pump. Supply air was produced from exhaust air, thus in the mentioned heat exchanger air already pre-cooled or pre-heated by the heat exchanger had to be cooled/heated further. Thus more extreme supply input (as ambient) air states could be established with the available cooling/heating capacity. A newly developed, high-efficiency Enventus type rotatry heat exchanger, with a 3 angstrom molecular sieve sorption coating, capable of heat-, and moisture transfer was installed within the test facility. Temperature and relative humidity values were measured with the help of three, humidity and temperature metering instruments, at given measurement points. The calibration of the instruments was performed by the producer. These temperature and relative humidity measurement points were located in the mid-plane of air ducts, 20 ±3 [mm] away from the end face of the wheel, along a circular arch with the same 145±5 [mm] radius. Inaccuracy in the measurement of these positions is a result of difficult accessibility, the rate of which has been estimated on the basis of measurements repeated several times. Data measured by the metering devices was recorded by a Testo480 data recorder. The Testo480 data recorder was connected to a PC via a USB port, thus using the Testo easyclimate 3.3 software, measured values could be plotted real time, showing the progress of graphs. Measured data sequences were saved with the software in the form of Microsoft Excel tables. The volumetric flow rate of supply air was measured by a Testo smartprobes 405i type hot-wire anemometer positioned in the centre line of the air duct, at point. The telescopic Testo 405i anemometer was positioned through a hole drilled on the side of the air duct, in order to measure the speed of air flow in the centre line of the duct. The metering device connected to a smart phone through Bluetooth radio connection. The Testo easyclimate 3.3 software running on the smart phone, received data from the device, and computed the volumetric flow rate from the averaged air velocity values measured, based on the dimensions of the air duct, which were entered in advance. The measurement location allowed for the physical model of realistic operating conditions, where maintenance of a steady volumetric flow rate of supply air is a requirement.

During the tests the boundaries of the state of exhaust air that could be permanently set were determined by the changing heat load of the laboratory and by the performance of heating and humidifying devices placed inside the exhaust duct. Based on test measurements, the maintenance of the exhaust air temperature between 20-26 [°C] and relative humidity range of 50-60 [%] proved to be possible. The settable temperature and humidity ranges supply input air (as ambient air) during measurements were determined by the technical properties of the test facility. An objective was to be able to carry out the measurements within the widest possible range. Due to the structure of the measurement system, the lowest and highest air temperature of supply air could be achieved at maximum wheel speed. This is due to the fact that supply air is produced by cooling-heating and humidification of exhaust air. Accordingly, under extreme operational conditions, with the increase of wheel speed, a part of the cooling/heating power input is not released into the environment, it rather pre-cools/preheats the discharged air, from which a greater enthalpy difference can be achieved with equal power input, than in the case of operational states with lower wheel speeds. The target value of supply input air temperature (reference signal) was connected into the SCMI-01 type PID controller. The PID controller used in the experimental investigation is manufactured specifically for the condensing unit produced by Sincalair manufacturer. Actually this controller can be used only for Sinclair products, but due to the imperfect data given by the producer it has to be tuned by setting the correct proportional, integral and derivative parameter values to achieve optimal energetic operation during every new installation [10]. Relative humidity of supply input air was regulated with the help of water atomizers. The ceramic insert spray nozzles were connected to the drinking water network by plastic pipes. The volumetric flow rate of water nozzles was first regulated by garden sprinkler ball valves, then for the purpose of more precise adjustment, by ½ ″ size, Herz type radiator valves. Spray nozzles were separately connected to two water outlets, therefore they did not influence the operation (water pressure) of the other in the

course of fine adjustment. The speed-voltage relation of the wheel was determined through measurement, using a type laser tachometer.

During the research the impact of the operational and thermal environmental conditions on their efficiency under steady-state conditions were also considered. The major findings obtained from this work are summarized as follows:

1. Effectiveness of the sorption wheel under wide ambient temperature and humidity range and different wheel rotation speed is determined by experimental tests.
2. Increasing the wheel rotation speed, effectiveness values are higher.
3. At low wheel rotation speeds, humidity transfer effectiveness is very low.
4. Low wheel rotation speeds affect sensible effectiveness much less under the investigated states of operation.

In this experimental study the correlation between the sensible, latent, total effectiveness under different ambient air temperature and humidity values and different rotational speeds of the wheel was investigated in detailed by experimental tests. Based on the results effectiveness - supply input air (as ambient air) condition charts were plotted that can be useful for researchers, developers and building service engineers in the practice [11].

The disadvantage of rotary energy recovery is the contaminant cross-contamination from the exhaust air to the supply air. This is very important for applications such as offices, schools, public institution where carbon dioxide (CO_2) cross-contamination can cause indoor air quality degradation. By this way the investigation the scale of CO_2 recirculation is also a research significant topic in rotary energy wheel operated in air handling units. To achieve this object the installed test facility was used at the Indoor Air Quality and Thermal Comfort Laboratory of BUTE University. A novel developed molecular 3Å sieve sorption wheel with high humidity transfer efficiencies is integrated into the experimental setup. In this research study carbon dioxide cross-contamination rate from the exhaust side into the supply side in sorption regenerative air-to-air rotary energy exchanger was conducted by experimental tests. During the study the correlation between the carbon dioxide cross-contamination, different rotational speeds of the wheel and different supply air volume flow rate was also investigated in detailed. Based on the results a rotation speed - carbon dioxide cross-contamination diagram is plotted that can be very useful for researchers, developers and building service engineers in the practice.

The major findings obtained from this research work are summarized as follows:

1. Carbon dioxide cross-contamination in air-to-air rotary energy recovery ventilation system degrades the indoor air quality.
2. Linear increasing tendency for carbon dioxide cross-contamination can be concluded increasing the rotation wheel speed and air volume flow rate.
3. Rotation speed - CO2 cross-contamination diagram is plotted that is useful for researchers, developers and building service engineers in the practice.

The novelty of the results is the correlation between carbon dioxide cross-contamination rate from the exhaust side into the supply side, and the rotation speed of the sorption wheel and the volumetric flow rate of air transferred in a wheel. The results were performed by experimental test and the correlation has not yet been investigated so much detailed in the course of studies conducted on the subject [12].

The student assistants, supervised by me, worked also hard in the research and submitted their research works to the Conference of Scientific Students' Associations ("TDK") that was organized on the 17th of November in 2016 at the Budapest University of Technology and Economics. Three students gave placements in our faculty with the under mentioned data:

Name of the MSc. student: Kristóf Burián
Title of the „TDK" research work: Investigation the energy saved by air-to-air heat-and energy exchangers
Placed I. in Building Service Engineering Section

Name of the BSc. student: László Poleczky
Title of the „TDK" research work: Investigation of the effectiveness and energy performance of rotary energy recovery unit
Placed II. in Building Service Engineering Section

Name of the MSc. student: Richárd Simon
Title of the „TDK" research work: Investigation the energy consumption of refrigerating chamber with novel developed DC inverter compressor controller
Placed II. in Process Engineering Section

Moreover one student, supervised by me, gave Special Award in our faculty:

Name of the MSc. student: Czirok Zsolt
Title of the „TDK" research work: Investigation the carbon dioxide recirculation in rotary energy recovery unit
Placement: Special Awarded in Building Service and Process Engineering Section at BUTE

All of them published their research work at National Conference of Scientific Students' Associations ("OTDK") organized at University of Dunaújváros between 6th to 8 th April 2017 and Richárd Simon got a special award there.

In the third year of the research TRNSYS simulation software was also purchased. In this year numerical investigations were performed on the annual energy consumption of heat and energy recovery ventilation systems. During this study the investigated heat recoveries were the fixed-plate heat exchanger, the run around coil and the heat-pipe technology and analysed energy exchangers are a sorption rotor (desiccant wheel) and rotary exchanger with lower humidity effectiveness without sorption coating. The effectiveness values of were selected from VDI 2071 standard. Using the ambient temperature and enthalpy duration curves generated by TRNSYS a developed detailed analytical method is presented to determine the annual energy saved of the ventilation systems. The calculation was achieved for three different climates EU cities. Within the frameworks of this research, energetic comparison studies were carried out for three cities of different climate (Palermo, as a city with warm climate; Krakow, a city with moderate climate, and Helsinki, a city with cold climate). The study material demonstrates the procedure of energetic dimensioning for the city of Palermo in detail considering publication limit, but the calculations were performed also for the mentioned two other locations. During the simulation 1000 m3/h constant volumetric flow-rate and balanced ventilation were assumed. For air density, a constant 1.2 kg/m^3 value was applied. In the course of studies during the cooling season, temperature regulation was considered only in the case of heat exchangers capable of heat transfer, thus the heat exchanger operates during the periods, when outside air temperature is higher, than the temperature of exhaust air. In the case of energy exchangers capable of heat-, and moisture transfer, enthalpy control was considered; consequently the energy exchanger operates until the enthalpy of outside air condition reaches the enthalpy of exhaust air. The amounts of possible energy saving, and the percentage values of such, are significantly higher during the heating season: in Palermo 44.600 MJ (66.86%), in Krakow 117.300 MJ (71.37%), and in Helsinki 156.700 MJ (71.74%) during a year, with a rotary heat exchanger with sorption coating. Furthermore, heat exchangers capable of only heat transfer also show more favorable values, with 10.000 MJ/year rate of savings possible: the least in Palermo, with a heat pipe heat exchanger (9.100 MJ/year), the most in Helsinki, with a plate heat exchanger (82.000 MJ/year). Results show, that both in terms of energy consumption and energy saving, the heating season is definitive. Looking towards cities with a warmer climate, the cooling season is also more and more significant, yet even in the city of Palermo the heating season is better. Looking at an entire year, the percentage values of savings possible with a rotary heat exchanger with sorption coating are: 70.25% in Helsinki, 69.22% in Krakow, and 55.28% in Palermo. The lowest values were received for heat pipe heat exchangers: 18.22% in Helsinki, 17.6% in Krakow, and 7.32% in Palermo based on this study [14].

The energy recovery potentials in ventilation systems were also investigated under different climatic conditions. The well-known heating degree day from the literature was updated using the weather data of cities with different climates from the past 40 years. As the novelty of this research with the developed procedure drawn up in this study, the energetic possibilities of heat recovery under various climate and operating conditions may be examined in more detail and more realistically than with the methods and available information of current engineering practices. To achieve this long-term and high definition weather data of several cities are processed in order to evaluate the possibilities of heat recovery on a daily and annual basis. Examined cities were selected on the basis of diversity of their climates, within the possibilities offered by the Wolfram Alpha database. Using the developed methods a large number of auxiliary tables have been generated on the basis of weather data, which may be utilized in the course of design work, and which allow for estimation of the expected realizable energy saving of ventilation equipment in any given month, during any time interval of operation in the function of the temperature and relative humidity of exhaust air, with a given expectation – applied decile curve [15].

Comparative energetic analysis with different calculation procedures was also performed during the investigation of a single family house. One of the methods that were used is the Ministry without Portfolio Decree No. 7/2006 for energy certification and MSZ-140-04 for energy demand calculations (by using WinWatt computer software) that are a widely used in the Hungarian practice by HVAC designers and experts. Passive House Planning Package (PHPP) simulation tool is also more and more common used PC software in Hungary due to the continuously tightening energy requirements. To see the differences and imperfections between these methods the heating, cooling and ventilation system was designed of a given single family house and the annual energy consumption was investigated with these methods. To perform the investigation in more detailed three

different heating systems were designed. In the first case the heat source is a condensing boiler operated with floor heating. In the other two cases the thermal systems are heat pumps with floor and ceiling heating. One of the heat pumps is an air-to-water system, the other one is a geothermal heat pump. The advantages of the heat pumps are that heating, cooling and domestic hot water energy is produced by only one equipment and efficiency. However comparing investment and operating costs for the heat pumps with gas boiler the payback time is very long based on this study. The investment costs, payback periods are investigated for the three different systems evaluating the results also with PHPP and WinWatt computer software tools in this study. From the research results it can be concluded that heat pump systems return their cost very slowly compared to the condensing boiler. Obviously these values are only approximate, as the time of return also depends on the family's living habits: how often, and how much they use the heating system, and also the change of energy's cost, both can cause significant deviation from the values calculated above. From the point of comfort feeling view in this passive house cooling is not necessary, as the proper heat insulation keeps warm outside. In spite of this fact cooling system was also designed as well considering also extreme climate conditions in summer. As the building has low energy needs, it is more reasonable to choose the condensing boiler with higher operational costs, which settling and where the necessary fittings are cheaper. As cooling is not really necessary, condensing boiler is the best and most economical technical solution [16].

The student assistants, supervised by me, worked also hard in the research and submitted their research works to the Conference of Scientific Students' Associations ("TDK") that was organized on the 16th of November in 2017 at the Budapest University of Technology and Economics.

Two students gave placements in our faculty with the under mentioned data:

Name of the BSc. student: László Poleczky
Title of the „TDK" research work: Investigation of the energy recovery potentials in ventilation systems at different climates
Placed II. in Building Service Engineering Section at BUTE

Name of the MSc. student: Péter Orbán
Title of the „TDK" research work: Investigation of procedure for sausage drying
Placed II. in Building Service Engineering Section at BUTE

Totally 16 pieces of publications were made in the topic during the research term financially supported by the National Research, Development and Innovation Office of Hungary [grant number NKFIH PD 115614], Budapest, Hungary. From this there are 4 pieces of international peer-reviewed scientific journal papers found in Web of Science database (WoS) with impact factors (IF); further 3 pieces of international peer-reviewed scientific journal papers which can be found in WoS and 1 in Scopus without IF; 2 pieces of national peer-reviewed scientific journal papers and finally 6 pieces of peer-reviewed scientific papers that were published at international scientific conferences.

Publications/years

I. Year

[1] Miklos Kassai, Mohammad Rafati Nasr, Carey J. Simonson: A developed procedure to predict annual heating energy by heat and energy recovery technologies in different climate European countries. **Energy and Buildings**. Vol. 109 pp. 267–273. DOI: 10.1016/j.enbuild.2015.10.008 (2015) (**IF=2.973)** (**WoS: Q1**)

[2] Miklos Kassai, Laszlo Kajtar: Investigation of Cooling Energy Saved by Air-to Air Heat-and Energy Exchangers in Different Climate European Countries. The 12th Rehva Word Congress Clima 2016 Conference, Aalborg, Denmark, May 22-25 (2016).

[3] Miklos Kassai: Energy demand and consumption investigation of a single family house, The 8th International Symposium 'EXPRES' on Exploitation of Renewable Energy Sources, effectivness, security and Carpathian PhD Student Meeting, Subotica, Serbia, March 30-April 02. pp 30-36. (ISBN: 978-86-919769-0-3) (2016).

[4] Miklos Kassai, Laszlo Kajtar: Cooling energy saved investigation of air-to-air heat-and energy exchangers, The 8th International Symposium 'EXPRES' on Exploitation of Renewable Energy Sources, effectivness, security and Carpathian PhD Student Meeting, Subotica, Serbia, March 30-April 02. pp 6-10. (ISBN: 978-86-919769-0-3) (2016).

[5] Miklos Kassai: A developed method for energy saving prediction of heat-and energy recovery units. **Energy Procedia**, vol. 85, pp. 311 – 319. doi: 10.1016/j.egypro.2015.12.257 (2016) (**WoS: Q4**)

II. Year

[6] M. Kassai: Energy saved of energy recovery ventilation system, 27th Annual and 9th International Conference Indoor Climate of Buildings 2016, Štrbské Pleso, Slovakia, (Edited, published by SSTP – Slovak Society of Environmental Technology, Bratislava) pp. 221-227. November 27-30 (ISBN 978-80-89878-03-1) (EAN 9788089878031) (2016).

[7] M. Kassai: Prediction of the HVAC energy demand and consumption of a single family house with different calculation methods. **Energy Procedia**, vol. 112, pp. 585 – 594. doi: 10.1016/j.egypro.2017.03.1121 (2017) (**WoS: Q4**)

[8] M. Kassai, P. Orban: Experimental investigation of procedure for sausage drying with newly developed DC refrigerators. Journal of Hungarian Building Services, vol. 2017/6., pp. 3-8 o., HU ISSN 1215-9913 (2017).

[9] M. Kassai: Numerical investigation on the energy consumption of ventilation system, EXPRES 2017, 9th International Symposium on Exploitation of Renewable Energy Sources and Effectiveness and Efficiency, Subotica, Serbia, March 30-April 01. pp 6-9. (ISBN: 978-86-919769-1-0) (2017).

[10] Miklos Kassai, Laszlo Kajtar, Jozsef Nyers: Experimental optimization of energy consumption for DC refrigerator by PID controller tuning and comparison with On-Off refrigerator. **Thermal Science**. DOI: 10.2298_TSCI170504188K. (2017) (**IF=1.093)** (**WoS: Q3**)

[11] Miklos Kassai: Experimental investigation on the effectiveness of sorption energy recovery wheel in ventilation system. **Experimental Heat Transfer**. vol.: 32, issue: 2, pp.: 106-120. DOI: 10.1080/08916152.2017.1397815. (2017) (**IF=1.687**.) **(WoS: Q2)**

[12] Miklos Kassai: Experimental investigation of carbon dioxide cross-contamination in sorption energy recovery wheel in ventilation system. **Building Services Engineering Research & Technology**. vol. 39(4) pp. 463-474. DOI: 10.1177/0143624417744733 (2018) **(IF=1.100) (WoS: Q3)**

III. Year

[13] Miklos Kassai: Energy Saving Investigation of Heat and Energy Recovery Ventilation Units, CIEM 2017, 8th International Conference on Energy and Environment, Bucharest, Romania, October 19-20. pp 177-181. DOI: 10.1109/CIEM.2017.8120762 (ISBN: 978-1-5386-3943-6; ISSN: 2067-0907) (2017). (**WoS**)

[14] Miklos Kassai, Laszlo Poleczky, Laith Al-Hyari, Laszlo Kajtar, Jozsef Nyers: Investigation of the Energy Recovery Potentials in Ventilation Systems in Different Climates. **Facta Universitatis, Series: Mechanical Engineering,** Vol. 16(2), pp. 203-217, DOI: 10.22190/FUME180403017K (2018) (**WoS**).

[15] Laith Al-Hyari, Miklos Kassai: Energetic Investigation of Energy Recovery Technologies in Air Handling Units. **International Review of Applied Sciences and Engineering**, Vol. 9., Issue 1, pp. 49-57 Print ISSN 2062-0810, Online ISSN 2063-4269, DOI: 10.1556/1848.2018.9.1.7, (2018)

[16] Miklos Kassai: Energetic Investigation of Low-Energy Family House, **Journal of Hungarian Building Services**, vol. 2018/5., HU ISSN 1215-9913, pp. 1-5. (2018)