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TRANSPARENT ELEMENTAL FACADE WITH AN INTEGRATED VENTILATION UNIT FOR A HIGH-RISE BUILDING – DEVELOPMENT AND EXPERIMENTAL VERIFICATION

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Abstract

The article documents the development of a modular transparent elemental facade. The cooperative development was realized in two areas, i.e., the development of facade ventilation units for an under-pressure ventilation system and experimental verification in a laboratory of a facade panel and optimization of its acoustic parameters. The task of controlled ventilation in modern residential buildings is to ensure the optimum quality of the interior environment and fulfill hygienic and thermal technical requirements that guarantee the comfort of the users. The paper discusses the development and experimental verification of atypical vertical ventilation units of an under-pressure controlled ventilation system for a residential high-rise building. A recommended concept for the facade´s details has been developed in relation to the ventilation system. Conceptual designs of alternatives to the air inlet openings of an under-pressure controlled ventilation system for the apartments with an atypical vertical geometry were proposed. An optimized alternative to air inlet openings in the bottom level of a vertical pilaster with the function of an air distribution channel for a ventilation system has been selected and developed. Laboratory experiments have verified the physical properties of the optimized alternative ventilation units of the under-pressure controlled ventilation system in their development cycle. The hydrodynamic regime of the air inlet openings of the controlled ventilation system has been verified by experimental research in a laboratory large rain chamber. The aerodynamic regime of a naturally controlled ventilation system was verified by experimental research in a large laboratory pressure chamber. The acoustic properties of the naturally controlled ventilation system were verified by experimental research in a laboratory´s acoustic chambers. The verified parameters of the ventilation units of the under-pressure controlled ventilation obtained by the experiment were compared with the design parameters. An experimental assessment of the mechanical, thermal and acoustical parameters of the elemental modular facade was carried out in a laboratory. At the end of the article, the results and conclusions of the laboratory experiment are summarized.

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Key words

- Transparent facade element,
- Facade ventilation unit,
- Under-pressure ventilation system,
- Development,
- Laboratory experiment.

1 INTRODUCTION

The principle of ventilation is to exchange indoor air for fresh outdoor air (Székyová et al., 2006). This movement of air happens as a consequence of the equalization of differences in pressure, which can be triggered in two ways: by forces of nature when we talk about natural ventilation or by means of fans, which represent mechanical ventilation. The role of ventilation is to ensure the optimum quality of the environment, i.e., meet the hygienic and thermo-technical requirements guaranteeing the comfort of the user. The emphasis is on the ventilation of all spaces with a minimum energy demand and air exchange rate. Insufficient ventilation may cause various skin diseases, respiratory diseases, allergies, cancer, and the like. In quantitative terms, the concentrations of pollutants in the air can be expressed in units of mass (mg/m^3), volume (vol. %, ppm = parts per million; ppm = 1 cm^3/m^3), and the number of particles per unit volume (dust). When there is inadequate ventilation, there is an increase in the relative humidity, CO_2 concentrations, presence of allergens, odors, and concentration of pollutants (Brager et al., 2000).

To meet the increasingly stringent standard requirements for energy performance and thereby reducing the operating costs of buildings, it is necessary to use energy-saving features of technical equipment and eliminate heat loss through building envelopes. The biggest losses are caused by the transmission of heat and ventilation in the form of uncontrolled air infiltration through a building envelope. Their elimination can be achieved by increasing the thermal and technical quantification of a building envelope and by increasing its airtightness.

On the other hand, there are hygienic requirements that set the required air exchange in the room, which is a key reason for the transformation of an unregulated method of ventilation to a controllable ventilation system. By proper dimensioning of a controlled ventilation system, we can ensure a required hygienic air exchange rate while avoiding excessive ventilation, which leads to unnecessary heat loss.

Depending on whether the equalization of the difference in pressure, and thus the air exchange, occurs due to natural physical phenomena or by using building environmental technology in the form of fans, we can distinguish between natural and mechanical ventilation. When the ventilation is provided by both forms of ventilation, for cases when we are no longer able to ensure the required hygienic indoor environment parameters by natural ventilation and mechanical ventilation is therefore required, we talk about hybrid ventilation (Székyová et al., 2006; Emmerich et al., 2001; Wahlström, 2006).

Mechanical ventilation is controllable and does not depend on the conditions of the outdoor climate. In terms of pressure conditions in a ventilated area we can distinguish between equal pressure mechanical ventilation and vacuum and pressure mechanical ventilation. The determining parameter is the coefficient of the ventilation balance ε, which is the ratio of the volume flow of the mechanically forced air supply V_p and exhaust air V_o:

$$\varepsilon = \frac{V_p}{V_o} \text{ (-)}$$

A controlled ventilation system with an air supply through the facade ventilation units allows for the manual or mechanical regulation of an air supply and extraction based on the input from the user of the room according to his preferences. The entire ventilation system can also be automatically controlled by temperature sensors, humidity, CO_2, the chemical properties of the air, or movement detectors (Lechner, 2009).

This system of regulation is more effective in terms of achieving a balance between the health requirements and the energy performance of buildings. To put it simply, the ventilation is only used so much as it is really needed. This system should be designed so that fresh air is supplied to the living space and waste air is extracted from rooms with increased humidity, odors and pollutants (toilet, bathroom, kitchen, etc.). The air supply to living spaces is secured by feeder vent valves installed in window constructions or in a peripheral wall, ideally above the heating units. The movement of air from room to room from where the waste air is extracted, should be facilitated by a construction design in the form of non-threshold doors or interior slots installed in doors or walls. Among the most important elements of controlled ventilation are the previously-mentioned air supply units, which greatly affect the operation of an entire controlled ventilation system through its design as well as its aerodynamic, acoustic, thermal and technical characteristics (De Dear, 1999). For this reason, it is important for the correct dimensioning of a regulated ventilation system to design appropriate air inlet ventilation units.

For the high-rise buildings of the Panorama City multifunctional center in Bratislava, the designers suggested a modular element facade with an atypical facade ventilation unit – Figure 1. Due to the fact that no available manufacturer of facade ventilation units (Renson, Aereco, Sigenia, Duco, Lunos, etc.) has a vertical type, it was decided to develop it. The subject of the article is the development and experimental verification in a laboratory of atypical ventilation facade ventilation units, their integration into the facade element and verification of the projected properties of the element with an integrated facade ventilation unit.

2 DESCRIPTION AND CONCEPT OF THE BUILDING ENVELOPE

The envelope of the two triangular high-rise towers of the Panorama City multifunctional complex in Bratislava is composed of facade blocks, i.e., facade elements of different shapes, functions, and parameters that were manufactured and assembled in factory conditions. The facade elements are designed around the Schüco USC 65 block system with a three-level sealing system and a horizontal functional gap that permits expansion movements due to the deflection of floor slabs in a range of ± 5mm. The most exposed linear parts of the elements were reinforced with steel in an inner static chamber for a characteristic wind load of 3.9 kN/m^2 (output from a laboratory simulation of the building model in a wind tunnel). The facade blocks are fitted with insulated double glazing with GUARDIAN SN 70/37 solar protection; the opaque parts of the spandrel consist of glued insulated panels with external aluminum sheets of a thickness of 3 mm, which is finished in RAL 9010; opaque fillings above the spandrel panels consist of insulated panel and tempered glass, which is finished in gray RAL 7037. All the thermal insulation fillings of the metal frames are designed and arranged alternately in layers for acoustic reasons and have various thicknesses and material densities. The facade blocks are fitted with hidden Schüco AWS 75.BS.HU+ sash windows with turn-tilt Schüco AvanTec concealed fittings and with an open limiter. In the facade blocks, there are special integrated vertical ventilation units of the vacuum system ventilation of the same construction depth as the element; they ensure a hygienic air exchange and acoustic comfort in the individual housing units. These ventilation modules were designed and experimentally verified in an extremely short time during applied research in collaboration with the Department of Building Structures at the Faculty of Civil Engineering in Bratislava.

The installation of the vertical ventilation unit into the facade element required atypical structural detail of the building facade technology. The client recommended solving problems with its outer zone in the form of a vertical pilaster at the height of the window part of the facade element – Figure 1.

This vertical pilaster had to ensure the following functions:

- Inlet of air into the under-pressure ventilation system
- Hydrodynamic water tightness of the facade element in the openings for the air inlet into the ventilation system
- Protection of the air inlet - a vertical distribution channel against birds and insects and hygienic maintenance or cleaning.

The optimization of the design of the vertical pilaster of the ventilation system, along with its structural development and experimental verification in a laboratory, were the key problems of the contractual cooperation mentioned.

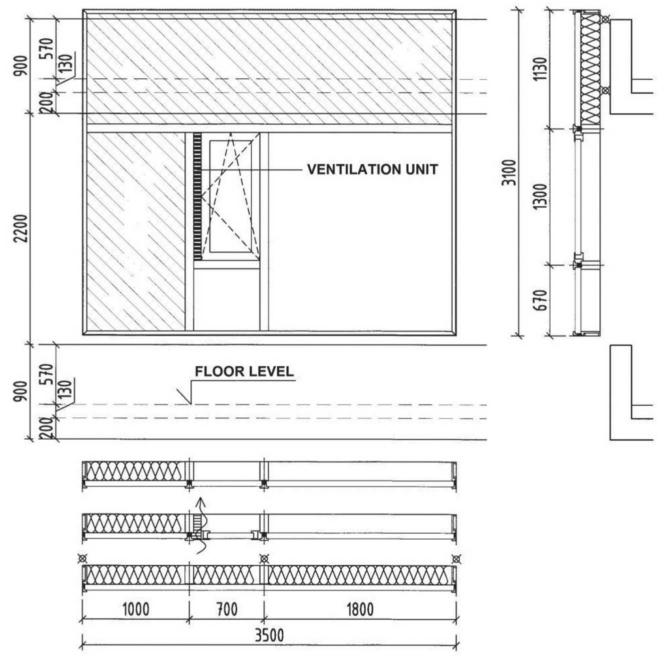

Fig. 1 *Scheme of the facade element with the placement of the ventilation unit*

3 PRINCIPAL CONCEPT OF THE VENTILATION UNIT

To solve the above-described problem, we recommended approaching the detail concept of the ventilation system conceptually according to the scheme in Fig. 2 and the following three zones:

Zone A: inner zone with the placement of acoustic insulation with a mechanically adjustable opening for the air current into the interior,

Zone B: central zone with the placement of highly efficient thermal insulation in a planar context with a thermal insulating double-glazed unit of the facade element (optimum position of the thermal insulation)

Zone C: outer zone in the form of a vertical pilaster protruding out of the facade plane with the function of the air inlet in the under-pressure ventilation system and with the function of a perfect rain barrier with a hydrodynamic regime "without any water penetration" from the complex effects of wind-driven rain.

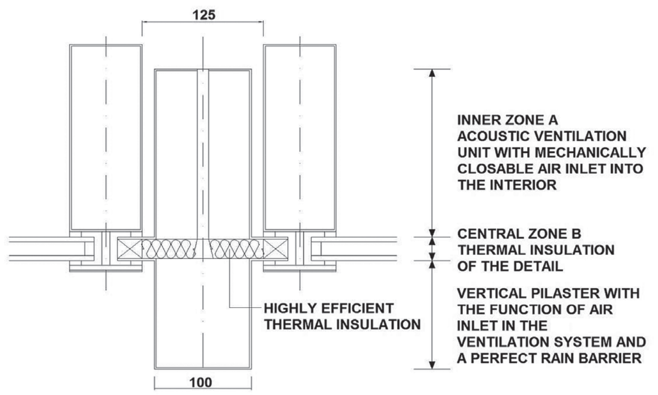

Fig. 2 *Recommended concept for a solution to the detail of the facade in relation to the ventilation system. Planar relation of the thermal insulating glazing system and the thermal insulation of ventilation unit.*

4 VARIATIONS OF THE DESIGN CONCEPTS OF AIR INLET OPENINGS OF AN UNDER-PRESSURE CONTROLLED VENTILATION SYSTEM

In our physical analysis of the vertical pilaster with the function of an air distribution channel for the ventilation system, we were interested in the question of "What is the optimal position for an air inlet in a vertical pilaster with the function of a distribution channel for a vertical ventilation system (a ventilation system with the acoustic system´s ventilation unit in a vertical position) ?".

There are three alternatives for inlet openings in a vertical pilaster with the function of an air distribution channel for a ventilation system :

- ALTERNATIVE I: Acceptable concept of the position of an inlet opening in the front plane of the vertical pilaster. This concept :
  - eliminates undesirable interference effects of air currents due to the distribution of pressures on the surface of the pilaster under the effect of wind from variable directions
  - has a distribution channel of the vertical pilaster that is filled with horizontal anti-rain or aerodynamic shutters, a water-conducting threshold, and a protective screen against birds and insects
  - requires cleaning of the air distribution channel together with the maintenance of the whole facade from the exterior
  - requires installation of the vertical pilaster with the function of an air distribution channel in the ventilation system while accepting the features of the facade system applied.

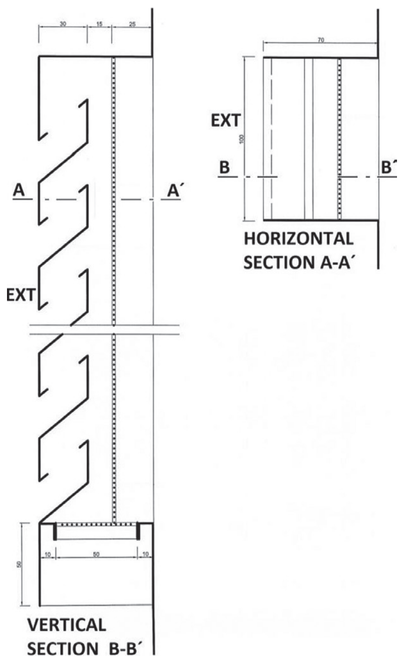

Fig. 3 *Structural design of a vertical pilaster with the function of an air distribution channel of the ventilation system with the application of classic anti-rain shutters in the front plane of the pilaster and a screen against birds and insects (EXT = exterior).*

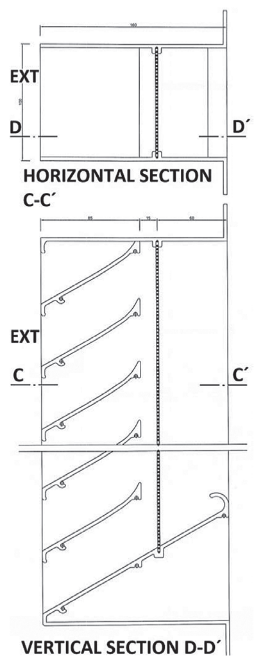

Fig. 4 *Structural design of a vertical pilaster with the function of an air distribution channel of the ventilation system with the application of aerodynamic shutters in the front plane of the pilaster, a water-conducting threshold, and a screen against birds and insects (EXT = exterior).*

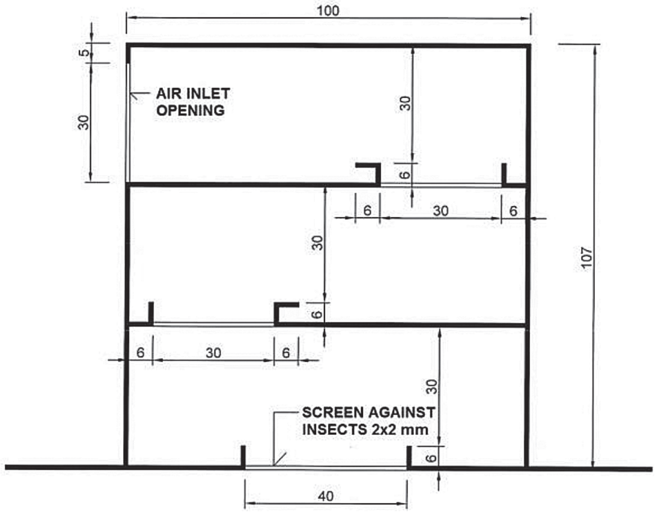

Fig. 5 *Structural design of a vertical pilaster with an air inlet opening in one of the side planes of the pilaster and with a system of inner partitions of a labyrinth with water-conducting grooves and a protective screen against birds and insects – a horizontal section through the pilaster*

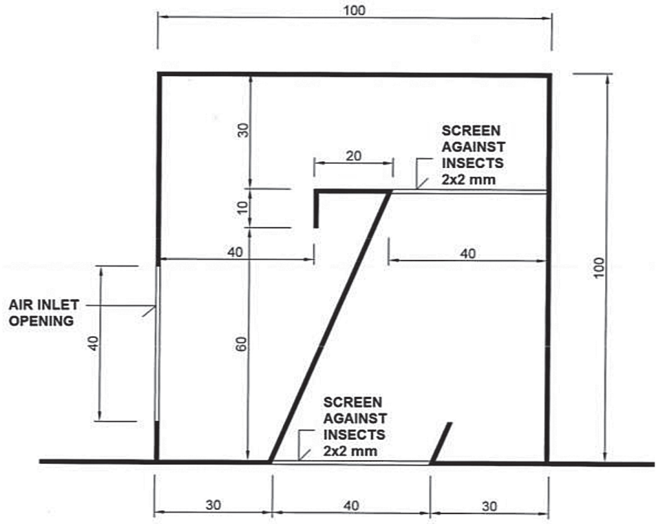

Fig. 6 *Structural design of a vertical pilaster with an air inlet opening in one of the side planes of the pilaster and with a system of inner partitions of a labyrinth with water-conducting grooves and a protective screen against birds and insects – a horizontal section through the pilaster*

A demonstration of the various options of the solution to the vertical pilaster problem with an inlet opening in the front plane with horizontal anti-rain or aerodynamic shutters and a protective screen against birds and insects is documented in Figures 3 and 4.

- ALTERNATIVE II: Acceptable concept of the position of an inlet opening in one of the side planes of the vertical pilaster. This concept :
  - partially eliminates the hydrodynamic load on the facade from the frontal air currents of the wind (perpendicular to the facade)
  - requires a distribution channel to be filled with partitions of a labyrinth system with water-conducting grooves and a protective screen against birds and insects.

A demonstration of the various options of the solution for the vertical pilaster problem with an inlet opening in one of the side planes with a system of inner partitions of a labyrinth with water-conducting grooves and a protective screen against birds and insects is documented in Figures 5 and 6.

- ALTERNATIVE III: The optimal concept of the position of the inlet opening in the bottom plane of the vertical pilaster – Fig.7. This concept :
  - represents the simplest modification of the vertical pilaster
  - eliminates all inconvenient situations from the pressures on the surface of the pilaster from the effects of wind from all variable directions and their consequences on the pressure conditions of the ventilation system
  - represents the simplest type of an anti-rain barrier system of the designed concept of the ventilation system from the complex effects of wind-driven rain.

Based on the consideration of the construction-production possibilities, the aesthetic appearance, and the economic demands of individual alternatives of a vertical pilaster with the function of a distribution channel for a vertical ventilation system, the designer, investor and contractor of the facade chose the implementation of ALTERNATIVE III.

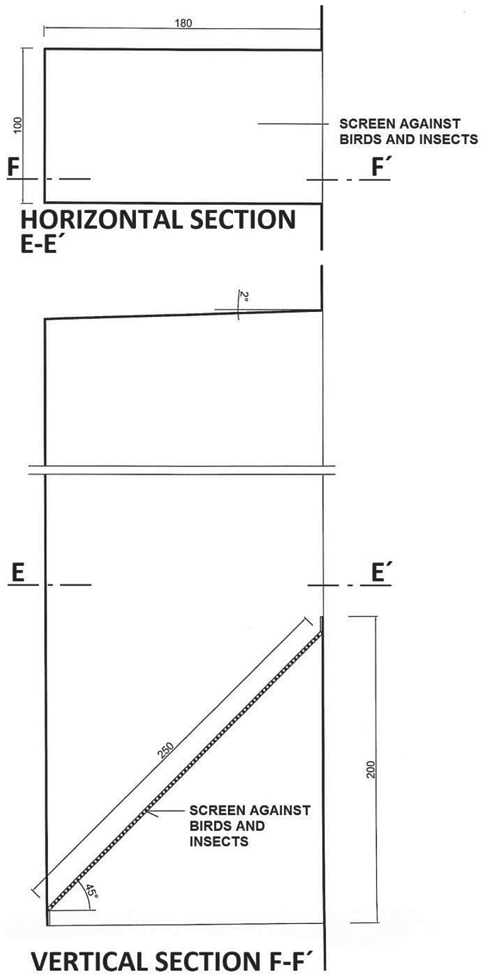

Fig. 7 *Structural design of the vertical pilaster with the function of an air distribution channel for the ventilation system with the optimal position of the air inlet opening in its bottom plane and a protective screen against birds and insects*

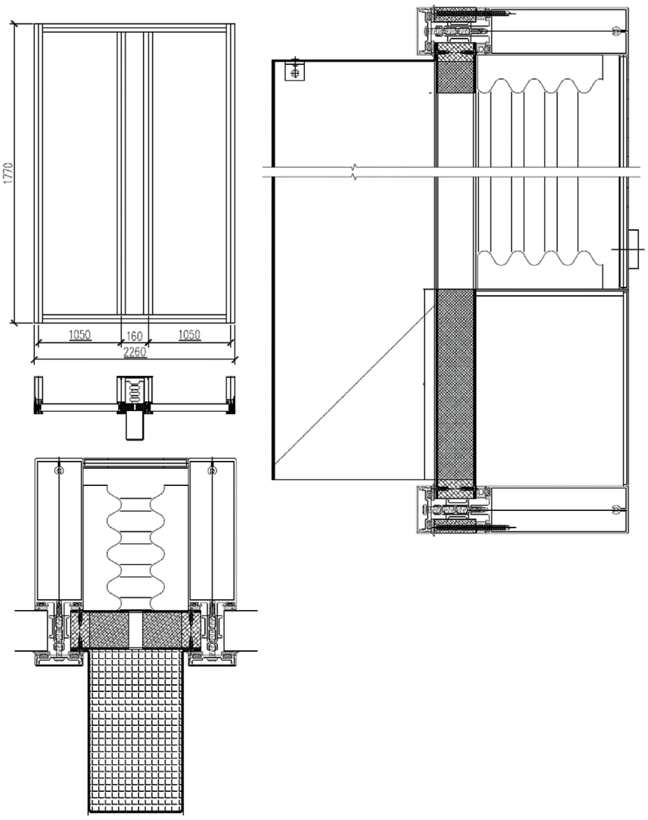

Fig. 8 *Measured sample of the optimized variant of the ventilation unit of the under-pressure ventilation system*

5 FINAL DESIGN OF THE FACADE VENTILATION UNIT OF UNDER-PRESSURE VENTILATION

After optimizing the shape, geometry, and structure of the outer zone of the facade´s ventilation unit, i.e., the optimized pilaster with the function of an air distribution channel, we proceeded to the structural design of the inner zone of the ventilation unit, the function of which is to serve as an acoustic and mechanically adjustable opening for the air inlet into the interior.

For this reason, the inner space of the zone between the facade posts of the element unit was filled with highly absorbable acoustic insulation and was enclosed on the inside by structural elements with mechanically closable apertures. The final solution to the ventilation unit is documented in Figure 8.

6 EXPERIMENTAL VERIFICATION IN A LABORATORY OF THE VENTILATION UNITS OF THE UNDER-PRESSURE VENTILATION

Part of the development of facade ventilation units for the under-pressure ventilation integrated into facade elements, which was realized at the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava, was also the experimental verification in a laboratory of their physical properties. The experimental research in the laboratory was realized on the final optimized variant of the ventilation units on the measured sample according to Figure 8 in the research laboratories for building physics and structures of the Department of Building Structures. The aim of the laboratory experiment was to verify the physical parameters of the proposed ventilation unit of the under-pressure ventilation and their confrontation with the design requirements.

An analysis of the internal structure of wind-driven rain in the locality of Bratislava in relation to the height of a building above the level of the terrain shows that for the high-rise buildings of the mentioned multifunctional complex (33 floors, height h ≈ 108 m), it is necessary to accept a wind gust velocity of $v_{N,BA,108} \leq 40$ m/s (Table 1).

In terms of ensuring the watertightness of the facade´s ventilation unit, our laboratory experiments showed a need for the application of dynamic insulation on the inlet to the vertical pilaster and in the area near the inclined screen against birds and insects. The dynamic insulation meets the following requirements :

- it is air permeable, i.e., it allows air filtration,
- it is water impermeable for the drizzling moisture dispersed in the air filtration,
- it performs the function of a temperature regulator of the air filtration. Depending on the temperature gradient line, infiltrating air thermally affects its thermal-insulating properties. This fact is important for the ventilation of a building interior, not only in terms of saving energy, but also in terms of the ecology of an indoor climate.

6.1 Experimental verification in a laboratory of the ventilation unit in terms of the hydrodynamics of buildings

The basic aim of this experiment was to investigate the hydrodynamic regime of the optimized variant of a vertical pilaster with the function of an air distribution channel for the under-pressure con-

Table 1. *The structure of wind-driven rain in relation to the height of a building above the terrain in the locality of Bratislava*

Building height h (m)	Height coeff. for wind w (-)	Height coeff. for wind-driven rain r (-)	Value of intensity of wind-driven rain $r_{v,H}$ (mm/h) (mm/s)	Intensity of wind-driven rain at wind gusts $r_{v,N}$ (mm/min) (mm/s)	Velocity of wind gusts in the int. struct. of wind driven rain $v_{w,N}$ (m/s)
3 floors h=10 m	1.00	1.0	14.6 0.0040	1.28 0.021	26.0
10 floors h=35 m	1.02	1.03	15.0 0.0042	1.34 0.022	26.0
20 floors h=70 m	1.31	1.16	17.0 0.0047	1.94 0.032	34.0
30 floors 105m	1.51	1.23	18.0 0.0050	2.37 0.039	39.0

trolled ventilation system in terms of the load from the complex effects of wind-driven rain in the climate conditions of Bratislava. The principal aim of the experiment was a geometric arrangement of the element, which is characterized by the impermeability of water.

The basics of the laboratory equipment for the mentioned experimental investigation was a large rain chamber to research the common phenomenon of water penetration through the details, elements and systems of the envelope structures of buildings (Figure 9). This device consists of :

- a circuit of the intensity of wind-driven rain (the density of wind-driven rain per hour r_v = 17 l/m^2.h for buildings up to 10 floors, r_v = 18 l/m^2.h^1 for buildings up to 20 floors, daily intensity of wind-driven rain r_v = 10 l/m^2.h in a duration of 6 hours); it also models the variability of the pressure factor of wind-driven rain, i.e., a moving system of nozzles
- a circuit of a constant water flow which, as a consequence of the intensity of wind-driven rain, falls above the site analyzed and moves downwards due to gravity (the density of the constant water flow r_{rovn} = 100 l/m.h)
- a circuit of air currents during wind gusts (wind gust velocity $v_{w,N}$ = 45 m/s, average velocity of wind among wind gusts v_w = 5.0 m/s)
- a circuit of the difference in air pressure of $15 \leq \Delta p \leq 700$ Pa for buildings up to 10 floors and $15 \leq \Delta p \leq 1000$ Pa for buildings up to 20 floors.

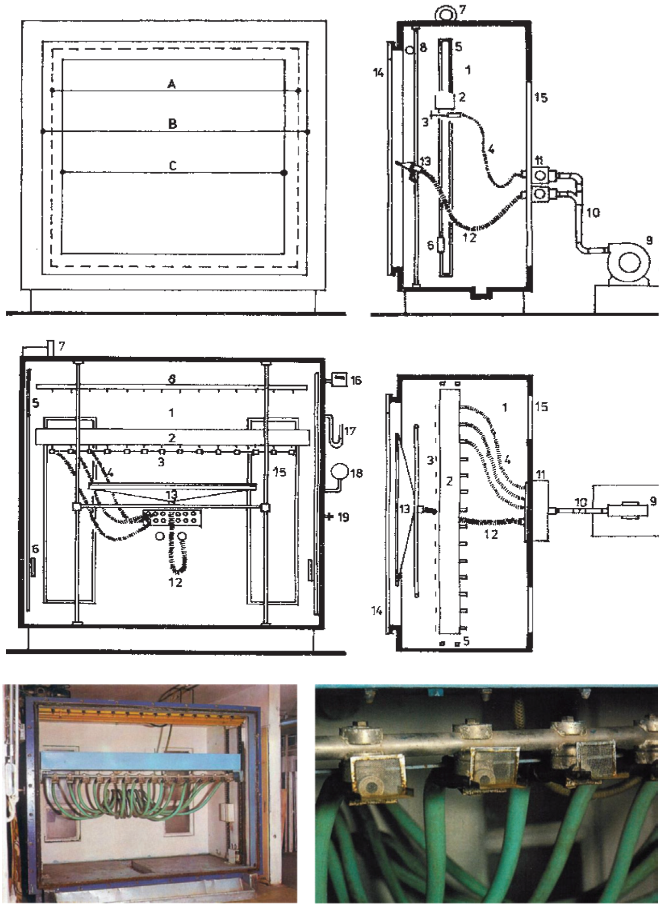

Fig. 9 *Large rain chamber for modelling the synergistic phenomena of the intensity of wind-driven rain, constant water flow, the differences in air pressure, and the air currents of wind*
1 – pressure chamber; 2 – circuit of the intensity of wind-driven rain; 3 – air dies with splitters; 4 –circuit of air currents during wind gusts; 5 – chain drive; 6 – counterweight; 7 – motor; 8 – circuit of constant water flow; 9 – ventilator; 10 – pressure pipe; 11 – cycle rate system – creator of wind gusts; 12 – pressure pipe; 13 – air die; 14 – masking panel; 15 – observation window; 16 – recorder; 17 – water manometer; 18 – mechanical manometer; 19 – safety pressure valve

The test sample measured, which was placed in a large rain chamber, is shown in Figure 10. The first measurements realized on the test sample of the hourly and daily intensity of wind-driven rain showed us that a test pressure higher than 110 Pa results in the penetration of water through the ventilation unit in the form of dispersed moisture, which arises from the shattering of rain drops that are transferred through the slot of the ventilation unit into the interior by the air current of the wind gust; after 6 hours of measurement, it formed a wet spot on the floor up to a distance of 220 cm from the rain chamber. After the measurement was completed, the inner acoustic insulation was wet, and a continuous layer of water was detected in the bottom part of the inner zone of the ventilation unit. We considered this condition to be unacceptable. The drizzling moisture transferred by air currents during wind gusts must not reach the inner zone of the detail. The effect of the transfer of the drizzling moisture from the shattering effect of the raindrops at the inlet into the distribution vertical pilaster must be stopped by the dynamic insulation.

The dynamic insulation meets the following requirements :

- it is air permeable, i.e., it allows air filtration. The level of air permeability q_V (m^3/m.h) or q_m (kg/m.h) of the interstice is necessary to be determined experimentally as a function of the difference in air pressure,
- it is water impermeable for the drizzling moisture dispersed in the air filtration. It is necessary to experimentally determine the water impermeability as a function of the intensity of wind-driven rain with the internal structure of the wind that characterizes a high-rise building (108 m),
- it performs the function of a temperature regulator of the air filtration. Depending on the temperature gradient, the air filtration affects its thermal insulation properties. This fact is important for the ventilation of the interior of a building not only in terms of saving energy but also particularly in terms of the ecology of the interior climate.

One problem remained with the position of the dynamic insulation within the ventilation unit in the form of the vertical pilaster with the function of an air distribution channel for the under-pressure controlled ventilation system to allow for maintenance without any major difficulties (trouble-free periodic replacement after a certain time) and the selection of a suitable material for the dynamic insula-

Fig. 10 *Overall view of the test sample placed in a large rain chamber*

tion to catch the drizzling moisture dispersed in the air filtration at the highest air flow rate possible.

The optimal position for its application in terms of its possible periodic replacement appears to be the inlet in the vertical pilaster with the function of an air distribution channel for the under-pressure controlled ventilation system, where a pair of parallel screens against birds and insects would be placed in an inclined position, between which would be the dynamic insulation from the interior side through a conveniently inserted service flap.

The next task was to find an optimal material for the dynamic insulation which would catch the drizzling moisture dispersed in the air filtration through the ventilation units at the highest air flow rate possible. Moreover, the material of the dynamic insulation must not degrade upon exposure to water (periodic moistening and drying of the material from the complex effects of wind-driven rain).

A total of 22 samples of possible materials for the dynamic insulation function were tested. In the first step indicative measurements were performed in a large rain chamber with an hourly intensity of wind-driven rain, the task of which was to exclude unsuitable materials for the dynamic insulation function. This meant materials that are not able to catch the moisture dispersed in the air filtration or materials that are able to catch the moisture but do not allow for sufficient air permeability for the ventilation unit. Suitable materials were afterwards subjected to experimental measurement in a laboratory in a large rain chamber using a 6-hour test with the daily intensity of wind-driven rain. Materials which passed the hourly and daily intensities of wind-driven rain without the penetration of rainwater in the form of dispersed moisture from the effect of rain drops shattering on the inner surface of the ventilation unit were afterwards experimentally investigated in a large pressure chamber for the air flow rate $Q_{ob,l}$ (m^3/h) in relation to the difference in air pressure Δp (Pa). On the basis of the above-mentioned measurements, an optimal material for the dynamic insulation applied within the ventilation unit of the under-pressure controlled ventilation system was selected. In terms of the hydrodynamics of buildings, 14 of the measured samples passed the criteria for the functioning of the dynamic insulation that were able to catch the aerosol moisture from the effect of raindrops shattering from the air flowing through the ventilation units without the penetration of rainwater into the interior.

6.2 Experimental laboratory verification of the ventilation unit in terms of the aerodynamics of buildings

The basic aim of this experiment was to investigate the aerodynamic regime of the optimized variant of the ventilation unit for the under-pressure controlled ventilation system, i.e., the quantification of the air flow rate $Q_{ob,l}$ (m^3/h) through the ventilation unit in relation to the difference in air pressure Δp (Pa) with the utilization of 14 variable samples of material for the functioning of the dynamic insulation which were able to catch the dispersed aerosol moisture from the effects of the shattering of raindrops from the air filtration through the unit. The laboratory experiment had 2 basic aims :

- exclude those material samples for the functioning of the dynamic insulation which show insufficient air permeability ($Q_{ob,l}$ < 50 m^3/h at a difference in pressure Δp = 20 Pa) and thereby optimize the selection of suitable materials for the functioning of the dynamic insulation
- verify the airtightness of the system of mechanically closable apertures in the inner zone of the ventilation unit.

The same test samples of the ventilation system were utilized for the laboratory experiment as for the hydrodynamic regime experiment in the large rain chamber; only the thickness of the acoustic insulation in the inner zone of the ventilation unit was optimized to keep the distance between both insulations at 15 mm, and the inner zone of the unit was closed by a structural element with mechanically controllable, closable ventilation apertures (Figure 11).

A large pressure chamber (Figure 12) was utilized for the laboratory experiment of the aerodynamic regime of the ventilation unit (Figure 11). It is basically an airtight chamber which is fitted from the front with a measured sample fixed to the masking panel. Air is pushed into the chamber through the air flow meter by the ventilator, which creates a difference in air pressure between the chamber and the outer environment, to which the measured sample is exposed. To maintain a specified constant difference in pressure, it is necessary to supply the chamber with a ventilator with the same amount of air filtered away through the leaks (connections, joints) of the measured sample. We can measure this amount with an air flow meter during a specified time period (e.g., 6 minutes) and subsequently convert that to 1 hour (10 times the measured volume of the air). That is how we can determine the volume of the air flow rate through the measured sample $Q_{ob,l}$ (m^3/h) at a specified difference in air pressure Δp (Pa). Based on the full range of the experimental laboratory measurements of the ventilation unit for the under-pressure controlled ventilation with the particular variants of materials for the functioning of the dynamic insulation in an open state, it can be stated that in terms of the measured volume of the air flow through the ventilation unit for the functioning of the dynamic insulation, 6 material samples met the criteria at which the measured volume of air flow through the ventilation units was greater than 50 m^3/h at a difference in pressure of Δp = 20 Pa.

The ventilation unit in the closed state showed a very good degree of airtightness where, at a difference in pressure of Δp = 1000 Pa, the volume of air flow was at the value $Q_{ob,l}$ = 13.6 m^3/h.

Overall, we can state that the ventilation unit with the application of the 6 mentioned material samples fully meets the design requirements for the functioning of the dynamic insulation and for the functioning of the under-pressure ventilation system.

Fig. 11 *View of the measured sample of the ventilation unit with the installed system of mechanically closable apertures in its inner zone fitted in the large pressure chamber*

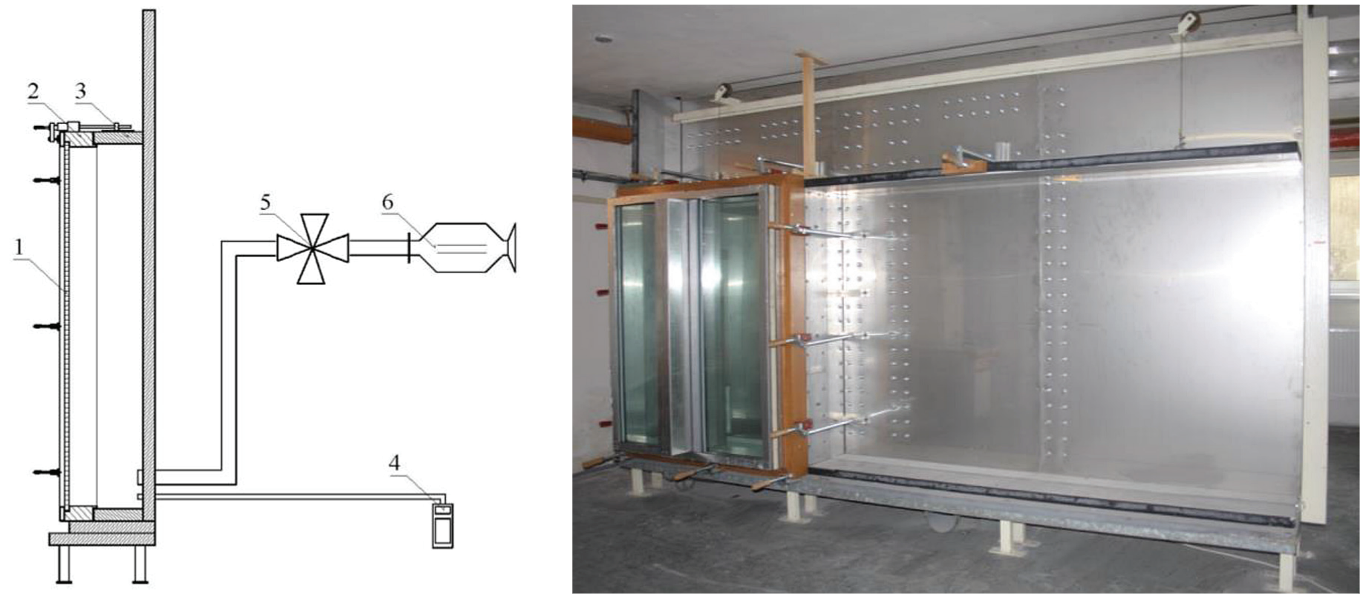

Fig. 12 *Scheme of the large pressure chamber*
1 – test sample, 2 – mounting frame, 3 – large pressure chamber, 4 – barometer, 5 – four-way valve, 6 – fan

6.3 Experimental verification in a laboratory of the ventilation unit in terms of the acoustics of the buildings

The basic aim of this experiment was to investigate the acoustic properties of the optimized variant of the ventilation unit for the under-pressure controlled ventilation system, i.e., the quantification of the standardized difference in the levels of elements $D_{n,e}$ related to a unit in the utilization of the 6 variable material samples for the functioning of the dynamic insulation, which were able to catch the dispersed aerosol moisture from the effect of the shattering of a raindrop from the air filtration through the unit and, at the same time, show the volume of air flow through the unit $Q_{ob,l}$ (m^3/h) $\geq$ 50 m^3/h at a difference in pressure of Δp = 20 Pa. The basic aim of the above-mentioned laboratory experiment was to optimize the selection of the material for the functioning of the dynamic insulation in such a way that the ventilation unit would meet the design requirements in its application in terms of the aerodynamics of buildings (air permeability), hydrodynamics of buildings (water impermeability), and building acoustics.

The acoustic chambers of the Faculty of Civil Engineering of SUT were built for testing the structures of windows and doors, partition walls, and ceiling structures in accordance with valid standards. The chambers are situated side by side and are one above the other with a volume of over 53 m^3 (Figure 13).

Upon the utilization of a loudspeaker system, the acoustic laboratories can create high levels of acoustic pressure in a K2 or K3 source room and receive an acoustic signal after its transmission through a measured element in the K1 receiving room. The levels of acoustic pressure are recorded by a microphone placed on a stand in six po-

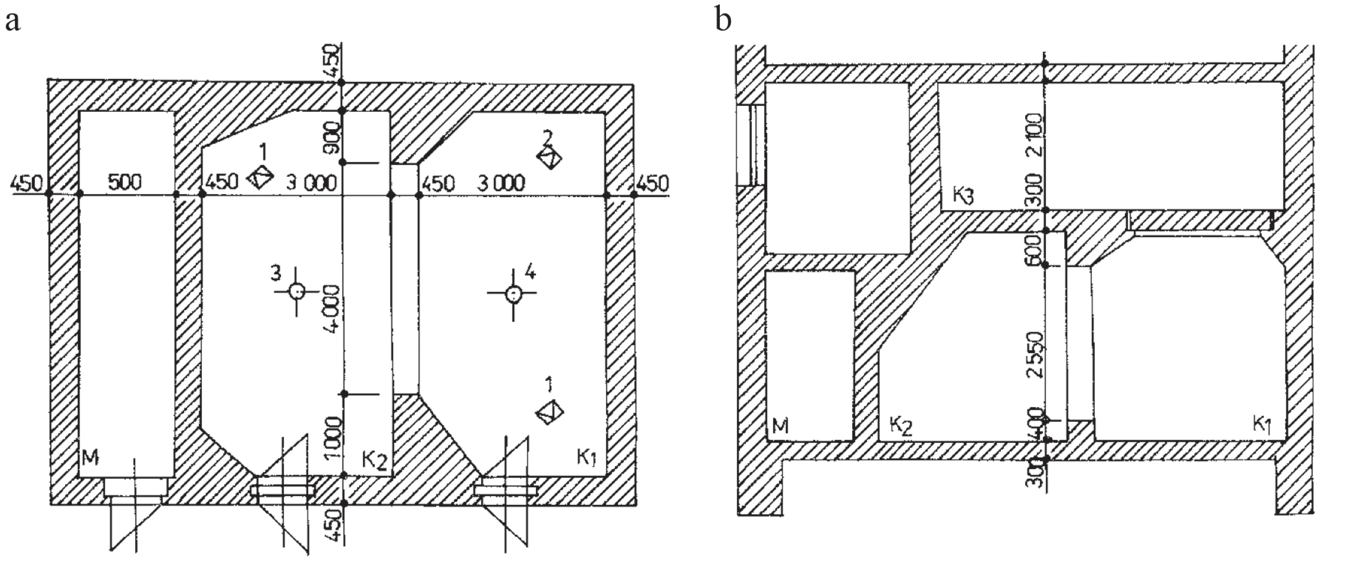

Fig. 13 *Structural scheme of the acoustic chambers of the Laboratory of Building Physics and Structures of the Faculty of Civil Engineering of SUT in Bratislava. a – floor plan, b – cross section of the chambers, K1 – receiving room, K2, K3 – source rooms, M – data acquisition unit, 1 – loudspeaker (for diffusion of the acoustic field), 2 – loudspeaker (for reverberation time), 3, 4 – microphone*

sitions in the source and receiving rooms, which ensures a representative measurement of an acoustic field. The acoustic pressure signal measured is recorded by a phonometer with a frequency range of 50 Hz to 5 kHz and is ready for further processing in a digital form. During the complex measurement, the level of background noise and the reverberation time in the K1 receiving room are measured in front of the actual element.

The acoustic performance of small technical elements, e.g., inlet air vents and other elements smaller than 1 m^2, such as profiles and niches for interior shutters, is expressed by a standardized level difference of the $D_{n,e}$ elements related to a unit. To characterize small technical elements, it is less appropriate to utilize the level of airborne sound insulation because the area of the measured element is not commonly well defined and the behaviour of the element is not necessarily related to the area of the element measured. For this reason, the behaviour of these elements is characterized by differences in the standardized level for a specific unit. Acoustic measurements of the ventilation unit in closed and open states were performed (Figure 14), and the standardized weighted level of the airborne sound insulation of the structural element of the ventilation unit was calculated according to STN EN ISO 717-1. In the closed state we achieved a value of $D_{n,e.w}$ (C,C_{tr}) = 57 (-2;-7) dB and the value $D_{n,e.w}$ (C,C_{tr}) = 43 (-1;-5) dB in the open state with 3 material samples for the functioning of the dynamic insulation. The design requirements for the acoustic properties of the ventilation unit, as expressed by the standardized weighted level of airborne sound insulation of the structural element,

Fig. 14 *Measured sample of the ventilation unit situated in the receiving room of the acoustic chambers*

were at a value of $D_{n,e.w,desired}$ = 48 dB in the closed state and at a value of $D_{n,e.w,desired}$ = 43 dB in the open state. From a comparison of the measured and design requirement values of the acoustic parameters of the ventilation unit, it follows that the experimentally verified ventilation unit fully meets the design requirements. Upon the application of an acoustic modification of the original vertical pilaster made of an AL sheet by taping its inner surface with a sound-absorbing self-adhesive 1.7 mm thick tape or by replacing it with a pilaster from Alucobond, we achieved an improved value with a difference in the normalised levels of the element, i.e., the ventilation unit in the open state by $D_{n,e.w}$ = 1 – 1.3 dB to the level of $D_{n,e.w}$ = 44 – 45 dB.

6.4 Summary of the physical quantifications of the ventilation unit

The developed ventilation unit utilizing appropriate materials optimized by the laboratory experiments for the functioning of a dynamic insulation :

- in terms of hydrodynamics, fully complies with the effects of wind-driven rain under the difficult boundary conditions of high-rise buildings (h = 108 m) by accepting the wind gust velocity of $v_{N,BA,108} \leq 40$ m/s without the penetration of rainwater, i.e., the criterion of watertightness is maintained,
- in terms of an aerodynamic regime, fully provides the desired volume air flow rate of $Q_{V,1}$ = 50 m^3/h with a rich reserve through the ventilation unit with a difference in air pressure of Δp = 20 Pa,
- in terms of acoustics, shows in a closed state the value of the element´s normalised level difference of the ventilation unit $D_{n,e.w}$ = 56 - 57 dB, which is a significantly higher value than the desired value $D_{n,e.w,desired}$ = 48 dB. The ventilation unit with a pilaster from Alucobond in the open state shows the value of the element´s normalised level difference, i.e., the ventilation unit $D_{n,e.w}$ = 44 – 45 dB, which is a higher value than the desired value of $D_{n,e.w,desired}$ = 43 dB.

The experimental laboratory verification of the physical properties of the ventilation units for the under-pressure ventilation system which have been integrated into the elements of transparent facades confirmed the fulfillment of the design parameters and thus completed their development cycle.

Fig. 15 *Views from the source room (A) and the receiving room (B) to the measured façade element situated in the aperture of the partition of the acoustic chambers*

Fig. 16 *View of the experimental laboratory testing of the facade elements in the laboratories of the Schüco Company in Bielefeld, Germany*

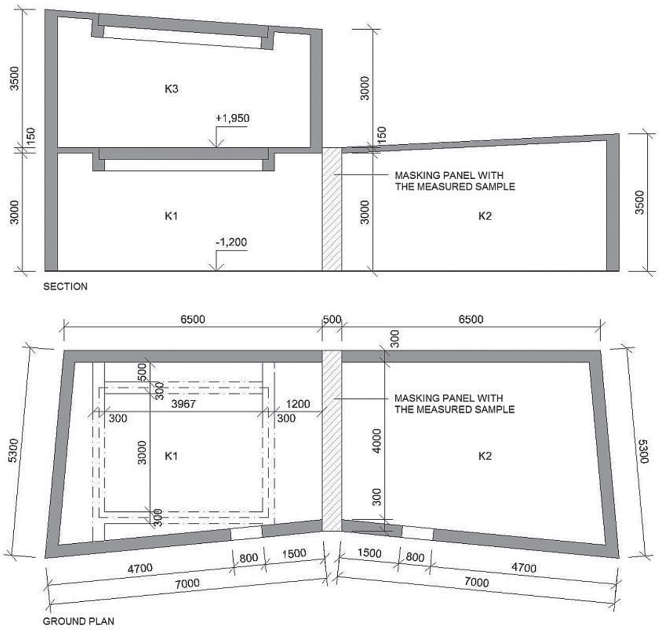

Fig. 17 *Acoustic chambers of the Slovak University of Technology in Bratislava, Faculty of Civil Engineering in the Central laboratory, Trnávka, Bratislava*

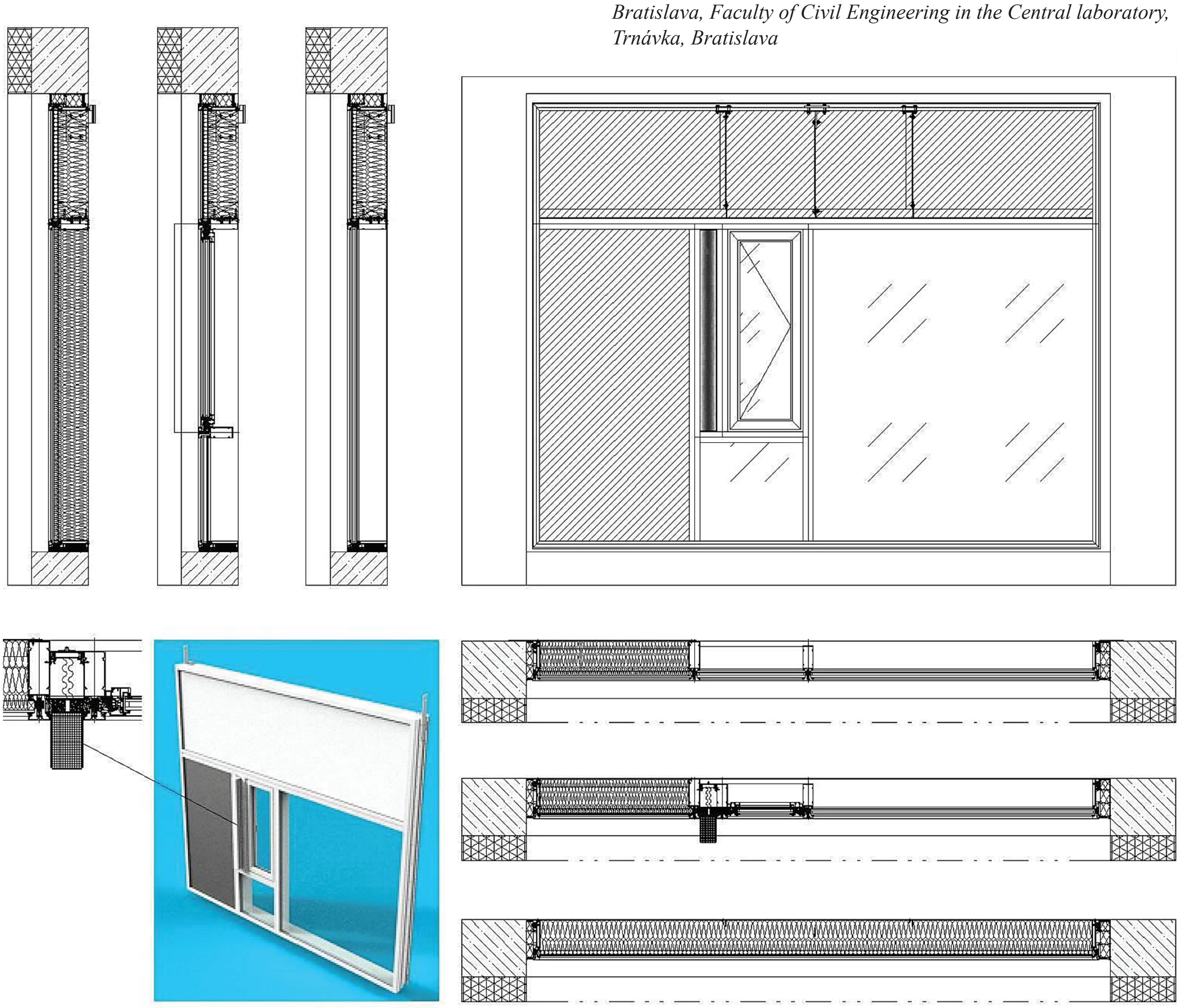

Fig. 18 *Design scheme of the measured sample of the elemental transparent modular facade*

Fig. 19 *Measured sample of the transparent facade element, view of the transmission rooms*

7 EXPERIMENTAL VERIFICATION OF THE FACADE ELEMENTS

The mechanical and thermal properties of the facade elements were experimentally verified in the Schüco Bielefeld authorized testing laboratory in Germany, and a test specimen with a size of 7000 mm x 6200 mm was assembled from four pieces of typical elements according to the relevant technical standards (Fig. 16). The pressure in the test chamber achieved an extreme value of 7000 Pa during the test of the mechanical properties of the anchoring system of the elemental facade. The experiment confirmed the following parameters of the facade:

- The infiltration and watertightness of the facade element in fixed parts: class AE and RE1200 (according to EN13830)
- Infiltration and watertightness of the operable parts of the facade: classes 4 and 9A (according to EN-14351-1)
- The thermal transmittance of the frame of the elemental facade U_f = 1.5 up to 1.8 W/m^2.K
- The resulting thermal transmittance of the elemental facade U_{cw}= 0.9 W/m^2.K.

The acoustic properties were experimentally verified by an authorized testing laboratory of the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava (Fig. 17) on a sample with dimensions of 3500 mm x 2750 mm (Fig. 18). The maximum value of the index of the airborne sound insulation required by the project of R_W = 43 dB was achieved by the assembled element with an integrated ventilation unit (in open and closed states) using a double glazed system (10 mm ESG HST SN 70/37 – 20 mm Ag – 12.76 mm VSG Conex 6.6.2).

All the experimental measurements confirmed the compliance with and fulfillment of the required parameters, which were tested on actual facade blocks.

8 CONCLUSIONS

The development and verification cycle of the new façade ventilation unit with atypical vertical geometry was realized in a relatively short time interval of 3 months. The façade ventilation unit has very high physical (aerodynamic, hydrodynamic and acoustic) parameters that exceed the projected parameters and is also suitable for high-rise buildings in locations with intense wind ratios.

The development and verification cycle of the elements of a modular block facade were followed by its manufacturing and assembly, which were undertaken by the Ingsteel Company Bratislava. In the period from September 2014 to April 2015, more than 35,000 m^2 of the modular facade were assembled, which represented more than 4,750 pieces of facade elements in a weight ranging from 200 to 700 kg each, the installation of which was provided by 130 to 200 skilled workers per day. The completed facade of the high-rise buildings of the Panorama City multifunctional center in Bratislava is shown in Fig. 20.

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***Fig. 20** High-rise buildings of the Panorama City multifunctional center*

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