JJMIE

Volume 16, Number 3, June. 2022
ISSN 1995-6665
Pages 429 – 437

Jordan Journal of Mechanical and Industrial Engineering

Modeling of Natural and Hybrid Ventilation System in the Building of High Heat Gains

Sylwia Wciślik*, Katarzyna Stokowiec

Kielce University of Technology, Faculty of Environmental Engineering, Geomatics and Power Engineering, Kielce, Poland

Received 16 Feb 2022 *Accepted 7 Apr 2022*

Abstract

Hybrid ventilation systems present many advantages compared to the natural or mechanical ventilation systems. In the case of buildings with significant heat gains, they seem to be the proper solution, if correctly analyzed and designed. The paper presents the calculations and study of the natural ventilation parameters with the possibility of including roof fans in the model glasswork in Kielce, Poland. The calculations for the optimization process were conducted using Ventos software. The limitations of the method include maximal values of air temperature at the top of the building, air velocity at the inlets and outlets, and negative pressure. Conclusions for the summer season arise that the most optimal solution ensuring the minimum internal temperature and air velocity conditions for the glassworks building is the use of wall inlets located on two levels. On the other hand, in winter conditions not all wall intakes should be open. Further analyses and simulations were performed for hybrid ventilation. Assessments confirm the accuracy and efficiency of using natural ventilation in facilities with significant heat gains, including glassworks.

Keywords: natural ventilation, hybrid ventilation, high heat gain building, glasswork.

1. Introduction

Building ventilation is observed to have a growing interest as a crucial aspect in each building project. The essence of installing such a system depends on its purpose: control of indoor air quality or improving summer comfort. The optimization problem differs varying from its concept. In case of indoor air quality control, the challenge appears during heating periods. The cooling demand is to achieve an optimal balance between air comfort needs and energy use. Whereas ventilation as part of a strategy of energy efficient cooling requires maximization of the air flow rates without creating comfort problems.

High heat gains are often properly associated with industrial building, where the managed process involves adequate equipment as well as environment with temperatures above 35^{0}C. Such working conditions are highly probable to cause both sudden as well as chronic health issues. Some of the existing buildings were constructed in order to support the technology, disregarding the systems that are supposed to provide thermal comfort for the employees. The visible discomfort may cause unwelcome physiological reactions such as heatstroke or fainting [1]. Not only the working conditions are of high importance. Buildings, especially with great heat gains, contribute to the energy consumption with Heating, Ventilations and Air Conditioning systems as elements that impact on anthropogenic climate change.

In case of high heat gains buildings, the solution to decrease the influence of high internal temperature appears to be hybrid ventilation, which may present a whole range of systems such as [2]:

- switching in time between natural ventilation and mechanical ventilation
- mainly a natural ventilation system (with support of mechanical ventilation if the pressure differences are not enough)
- mainly a mechanical ventilation system (with support of natural ventilation if the available natural forces are optimal).

The research conducted in the area of hybrid ventilation has increased [3]. But still, the number is relatively small, therefore the studies in this field seem to be a promising investigation. The trends discuss mostly thermal comfort internal air quality and numerical simulation.

The improvement of thermal parameters inside the building includes a well-designed ventilation system. The ventilation method that is widely applied [4] as well as easily employed in case of ventilation modernization is hybrid ventilation. This system creates a uniform air temperature as well as constant pollutant concentration by means of mixing flowing outdoor and indoor air. The hybrid ventilation system may work in two modes. The natural ventilation system is suitable when the outdoor air temperature is sufficient to obtain proper density differences. Therefore, this solution uses less energy than mechanical ventilation since the mechanical ventilation

* Corresponding author e-mail: sylwiazw@tu.kielce.pl.

mode in hybrid ventilation concept is applied only to compensate

for the shortcomings of natural ventilation by making the wind velocity adjustable. On the other hand, hybrid ventilation is less challenging than the natural one, since it relies on outdoor air conditions which need to be better than the indoor ones in terms of temperature, humidity and contaminants levels. Gravitational ventilation is subject to good wind speed and direction to enable an effective air flow through the building. The still pressure coefficient and normalized turbulent kinetic energy strongly influence natural ventilation [5].

The most appropriate for hybrid ventilation were discussed to be warm temperate climates [6]. They present a good alignment between buildings cooling needs and the mildness of the climate. An effective building operation is also obtained by means of well-managed methods for control of hybrid ventilation system that usually includes classical control methods. In case of temperate climates, the hybrid ventilation may save operational costs: even up to 60 (offices) -70% (schools), whereas in hot arid around 50% or warm humid only 28% [7]. In temperate climates, the strategy is generally achieved by maximizing natural ventilation. In dry tropical climates, potential savings are gained by implementing a cooling strategy.

Hybrid ventilation is widely researched in case of residential buildings. A possible solution suggested is a compilation of air intake through automatically regulated louvers in bedrooms and living rooms, both natural and mechanical exhaust: natural exhaust in bathrooms and fan exhaust systems in kitchens. The experiments in Portugal proved that such systems may provide adequate ventilation rates. PMV and PPD factors indicated that the operative temperatures satisfy the thermal requirements [8]. In multi-residential building, highly favorable are systems with the control strategy that maximizes the use of natural ventilation when outdoor conditions are optimal [9]. In Latvia hybrid ventilation system is proposed not only for new residential buildings but also during renovation processes [10].

The performance of a hybrid ventilation system with heat recovery for low-energy buildings with solar collectors and heat pump indicated many advantages of such a system [11]. In general, the system is based on natural ventilation with a fan utilization when natural driving forces are not sufficient. The heat of the exhaust air is recovered in an air-to-water heat exchanger and the heated water is applied to preheat the fresh air. Also, the system strongly reduces energy consumption due to the usage of sewage tank, where the sewage water from showers, sinks, washing machine etc. is stored temporarily. The heat recovered from the sewage system with solar energy is used to heat the ventilation air and preheat the cold water for domestic use. All the novel methods make the entire system more efficient than the traditional fan-assisted hybrid ventilation.

The solar adsorption refrigeration system was also evaluated experimentally and theoretically as a solar cooling system [12]. Analysis also includes determination of the duct layout, and the size of ducts in high-rise buildings [13]. The process was validated with network simulation performed in the 20-storey building.

Apart from residential buildings, the study also includes a comprehensive school in Helsinki [14]. Improvement of fan-assisted hybrid ventilation system allowed a decrease in concentration of indoor-generated pollutants. Innovative methods of hybrid ventilation may be also introduced in hospitals [15]. These solutions could be applied in most climate conditions and present high flexibility, and energy saving.

The experiments were also conducted for Chinese conditions for hybrid ventilation and proved thermal comfort for different outside conditions, since PMV index is between -0.5 and 0.5 [16].

In case of a multi-heat-source industrial plant a buoyancy-driven hybrid ventilation system was investigated and the effects of the above-floor inlet height and exhaust velocity were analyzed [17].The results of study indicated that properly increasing the above-floor inlet height can improve the working area thermal environment with the optimal above-floor inlet height was identified at 1.2 m.

Hybrid ventilation system may be equipped with a heat exchanger. The measurements results show the possibility to develop a ventilation system driven by natural forces including heat recovery [18]. The experiments include analysis of earth-to-air heat exchanger technology. They proved that new model are required for hybrid ventilation, since the existing ones are not appropriate to simulate such conditions [19]. The hybrid ventilation, with cold water circulating through the internal heat exchanger, managed to cool incoming air with temperatures of 25 to 35°C down to a comfortable 20°C [20]. It can be added that in such ventilation systems heat can be efficiently recovered using e.g. phase - change heat changers [21]. Another study develops a solar-driven hybrid ventilation system suitable for use in domestic buildings or classrooms with a wall-mounted convector unit that distributes fresh outside air heated or cooled with water circulating in a coil. This allows a constant supply of clean, filtered, conditioned air. The renewable energy sources are used to provide the cooling and heating of water [22].

An example of rooms with significant heat gains are bathrooms in glassworks, with bath and shift furnaces (glass melting tanks). Glass is made by melting, at a temperature of 1573°C, soda - sodium carbonate, Na_2CO_3, quartz sand SiO_2 and calcium carbonate $CaCO_3$, and then rapid cooling of the product. The general technological cycle related to the production of glass is presented in Figure 1. At each stage, there are different phases characterized by variable conditions of temperature, atmosphere and gas pressure.

In large-scale hall-type facilities - which include, among others glass and metal works, waste incineration plants and power plants - the burden of technological heat gains is often a significant problem, especially during the operation of plants in the summer. On one hand, we want to provide relatively optimal conditions for thermal comfort for employees, on the other hand, we should take into account the permissible operating temperature of the roof structure. If it is exceeded, it may cause material fatigue due to the deformation of nodes of light steel structures, which are very popular nowadays [23, 24]. As it turns out, the best and optimal solution to remove the air polluted with heat in such facilities is natural or hybrid ventilation. This is the result of the required significant amount of air changes, in the order of 30÷40 l/h, and thermal draft, which eliminates the influence of horizontal air movements - wind - caused by the pressure difference and differences in the shape of the surface.

Literature studies rarely deal with the subject of ventilation in industrial buildings with significant dimensions and heat gains. Therefore, the article aims to mainly optimize the operation of natural ventilation in a model glassworks located in Kielce, 50.87°N / 20.63°E / 274 m above sea level (Poland) that belongs to the IInd climatic zone of the summer period, as shown in Figure 2. According to the PN-76/B-03420 standard [25] used to design ventilation systems in the given location, the following calculation parameters of the outside air are assumed: dry thermometer temperature: θ_e=30°C, relative humidity RH = 45%, moisture content x = 11.9 g/kg. Moreover, it is also shown how devices of hybrid ventilation may affect outgoing natural volumetric flow of air and temperature under the roof.

During summer, in the analyzed region, outside the dry bulb, temperature can reach even 36°C. It seems to be suitable to make also appropriate simulation for the conditions, which derives from the most actual meteorological data, which has also been calculated in the paper. Likewise, computational analysis for winter time shows and confirms that natural ventilation works more efficiently during cold days.

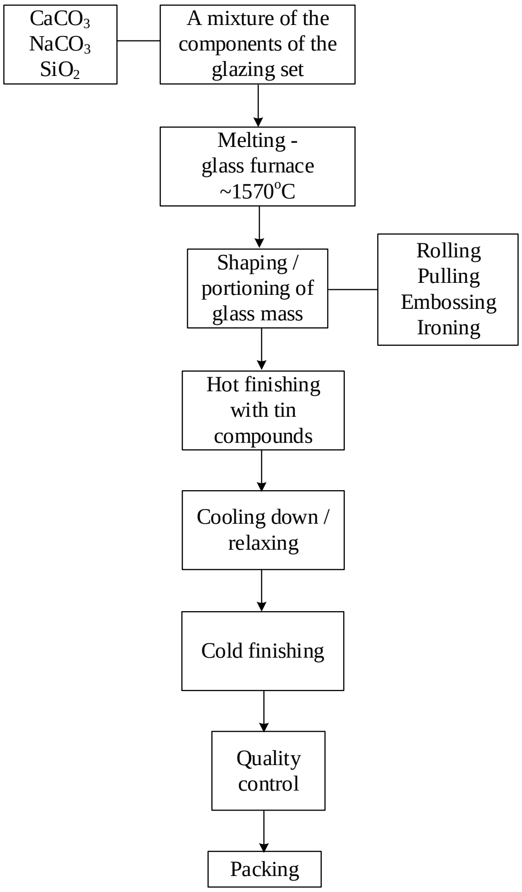

Figure 1. Technological process of glass production.

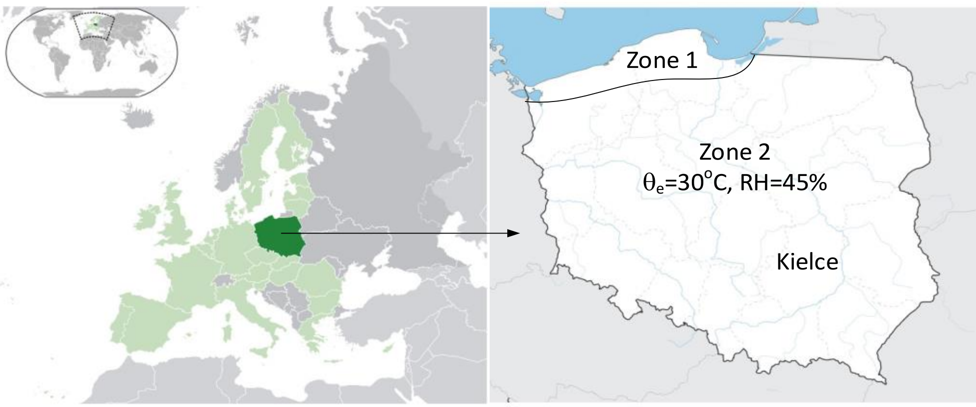

Figure 2. The division of Poland into climatic zones for the design of ventilation and air conditioning systems [25].

2. Methodology

In the paper, the Ventos software [26] was used to calculate and analyze the parameters of natural ventilation with the possibility of including mechanical elements and taking into account the influence of wind. The model glassworks is built on a cuboid plan with an average height of h_{av}=21 m. Basic input data are given in Table 1. The calculations were made assuming that the building temperature is stable, i.e. the sum of heat gains in the room is equal to the sum of heat fluxes discharged by ventilation ($\Sigma\Phi_G=\Phi_{v,out}$). Heat gains through external walls were omitted due to their small share compared to heat gains from technology ($\Sigma\Phi_{G,ex.wall}<<\Phi_{G,tech}$). The parameter VB - degree of obstruction - appearing in Table 1 – indicates the share of technological devices in the total cubic capacity of the room; usually this parameter is in the range of 0.2÷0.6. Recommended average wind speed around the building is set to 0 m/s, that is the worst possible option for natural ventilation. Inlet air temperature that is supplied to the building volume for the summer period (without air heating as it is for the winter time) is usually equal to external temperature. Total assumed heat gains from technology is set to 11.2 kW and derives mainly from operation of the blast furnace. Degree of room loading, depends mainly on the size, location or geometry of the heat source and the heat exchanger type; this parameter is usually adopted from the range of μ_T=0.2÷1.0, and for glassworks it is 0.3. In addition, it is assumed that the maximum air temperature under roof at the h_{max} height, due to the safety of structural members, should not exceed 70°C; the calculations also took into account radiation heat gains from technological systems and thermal devices. Another limitations are air velocity in the supply opening, $v_{in,max}$= 1.5 m/s and negative pressure value not exceeding Δp = 50 Pa (which makes it possible to open the door easily). Limitations in modeling of the ventilation system in a glasswork are presented in Table 2.

Table 1. Basic input data for modeling of the ventilation system in a glasswork.

Input data – description	Symbol, unit	Value
Room length	a, m	50
Room width	b, m	50
Maximum building height (roof ridge)	h, m	22
Mean room height	h_{av}, m	21
Degree of obstruction	VB	0.4
Mean wind speed	U∞, m/s	0.0
Inlet air temperature	θ_{sup}, ^{o}C	30
External temperature	θ_{ext}, ^{o}C	30
Total thermal load from the processes	Φ_G, kW	11,200
Degree of room loading	μ_T, -	0.3

Table 2. Limitation in modeling of the ventilation system in a glasswork.

Input data – description	Symbol, unit	Value
Temperature under top	t_{out}, ^{o}C	70
Air velocity in opening	v_{in}, m/s	1.5
Air velocity in outlet	v_{out}, m/s	10
Negative pressure	p, Pa	50

After determining the basic input data, the following parameters of air supply openings - wall air intakes - and roof exhaust - for the summer period (openings of natural ventilation - intakes and outlets) are assumed:

- total amount of the devices,
- the height of center of opening above the baseline/the ground,
- coefficient of the flow C_v that depends on the device and its aerodynamic active surface; usually this parameter is set in the range of C_v=0÷1,
- the width and height or length of the inlet into a single device,
- coefficient of the wind resistance C_w [-] that derives from the static and dynamic pressure ratio and wind parameters.

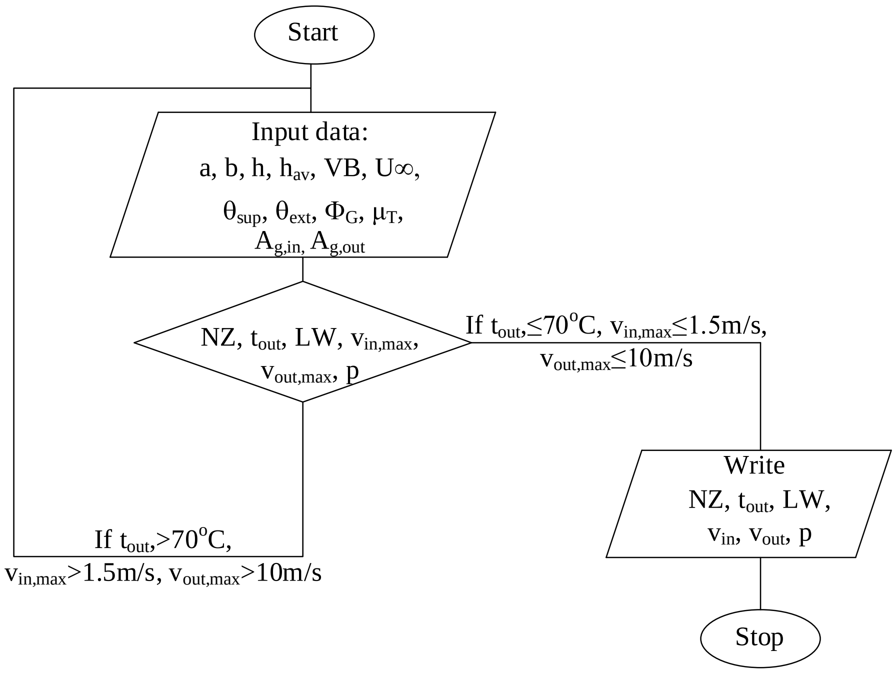

Figure 3. Block diagram of the calculation algorithm during simulation in Ventos.

3. Results

After defining the basic input data as well as geometric and aerodynamic parameters for the supply and exhaust openings, and after determining the accuracy of the next iteration of the calculation as 0.1, the following is calculated: inter alia, the maximum temperature under the roof, the amount and velocity of air flowing through each opening, the number of air changes, as well as the height of the pressure equalization zone in the building and the air pressure difference to the outside pressure. The calculations are made using the method of successive approximations so as not to exceed the limitations described in Table 2. The number of intakes and outlets and their total geometrically active surface are set in such a way as to achieve the minimum requirements specified therein.

In the first stage, the simulation was carried out with the assumption that the design external air temperature for Kielce, defined as standard, is θ_e=30ºC [25], and all designed supply and exhaust openings are open. The results of this simulation are shown in Table 3.

4. Discussion

Based on the calculations, it is concluded that the most optimal solution is that numbered 7 (wall inlets are located on two levels – 2.9 and 4.9 m from the ground: 27 on each of them; the number of roof vents is also 27), where the total active area of the inlets is 77.76 m^2, and outlets of 71.08 m^2. The pressure equalization zone is located more or less in the middle of the hall (which is the most desirable case) and is 11.63 m (see Fig. 4), the supply velocities were not exceeded and amount to v_{in}=1.4 and 1.2 m/s, respectively, for air intakes located on two levels, and the maximum temperature under the roof of the hall is approx. 67ºC. Figures 5 and 6 show how the aerodynamic surface of the intakes and outlets affects the height of the pressure equalization zone. Air velocity in outlets does not exceed v_{out} = 3.3 m/s in any case.

Table 3. Results of computer simulation of the natural ventilation system in a glassworks for summer time and external temperature of θ_e=30ºC.

No.	1	2	3	4	5	6	7	8
Supply air intake, quantity	10	15	30	30	30+30*)	28+28*)	27+27*)	25+25*)
Exhaust air outlet, quantity	10	15	15	25	28	27	27	27
Unit geometric area of the inlet, m^2	2.0 x 1.8							
Unit geometric area of the outlet, m^2	1.5 x 2.7							
Opened for incoming air (geometric) $A_{g,in}$, m^2	36	54	108	108	216	201.60	194.40	180.00
Opened for incoming air (aerodynamic) $A_{w,in}$, m^2	14.40	21.6	43.2	43.20	86.4	80.64	77.76	72.00
Opened for outgoing air (geometric) $A_{g,out}$, m^2	40.50	60.75	60.75	101.25	113.40	109.35	109.35	109.35
Opened for outgoing air (aerodynamic) $A_{w,out}$, m^2	26.33	39.49	39.49	65.81	73.71	71.08	71.08	71.08
Incoming natural volumetric flow of air, V_{in}, m^3/h	353 753	473 265	616 882	728 029	977 420	944 195	933 347	912 994
Outgoing natural volumetric flow of air, V_{out}, m^3/h	467953	587545	731296	841932	1091407	1058284	1048959	1025673
Air displacement (per hour), LW, 1/h	10.8	14.45	18.83	22.22	29.84	28.82	28.49	27.87
Temperature under top, t_{out}, ºC	127.9	103.1	86.1	77.6	65.4	66.7	67.1	68
Air velocity in openings, v_{in}, m/s	2.7	2.4	1.7	2	1.3 i 1.2	1.4 i 1.2	1.4 i 1.2	1.5 i 1.3
Height of the neutral zone from ground NZ, m	16.72	16.89	11.46	16.02	11.1	11.33	11.63	12.33

*) the inlets are located on two different levels

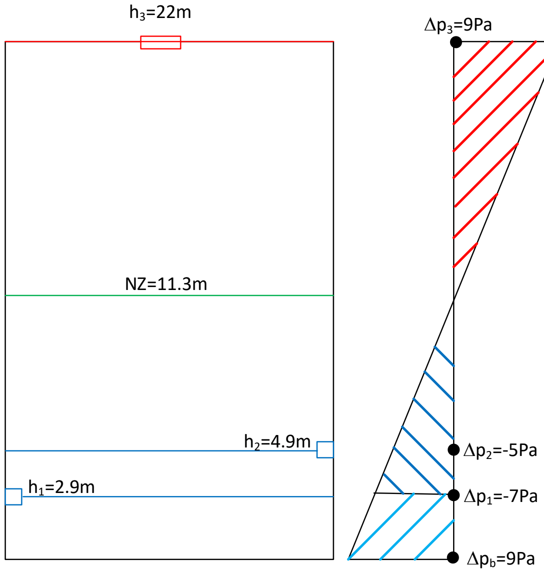

Figure 4. Height of the neutral zone from ground/pressure equalization zone, NZ for summer time.

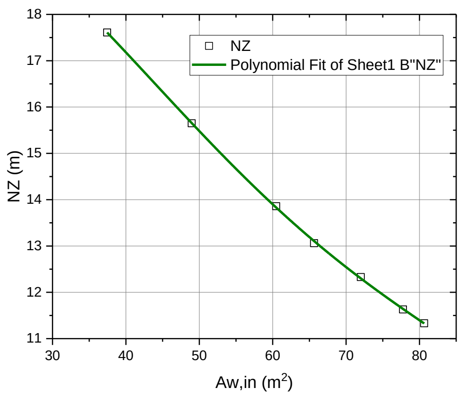

Figure 5. Height of the neutral zone from ground in the function of the air intakes aerodynamic area, NZ($A_{w,in}$).

However, the analysis of climatic conditions shows that the design temperature θ_e=30^{o}C is often exceeded, which may result in a significant decrease in the efficiency of ventilation systems, shutdown of production processes or, in extreme cases, even damage to structural elements. Based on the meteorological data [25], it can be noticed that the temperature of the dry bulb in the Kielce area, in the summer period, may be as high as 36^{o}C (data for July 2021). In such a case, the air temperature under the roof of the model glassworks would be exceeded and would be approx. 74^{o}C. Therefore, it would be necessary to increase the aerodynamic intake area by 34.6 m^2 ($A_{w,in}$= 106.56 m^2), and the outlets by approx. 5.26 m^2 ($A_{w,out}$= 76.34 m^2); the temperature under the roof would then be 69.7^{o}C, and NZ = 9.7 m; the total number of intakes on both levels is 38+36, and the number of outlets is 29.

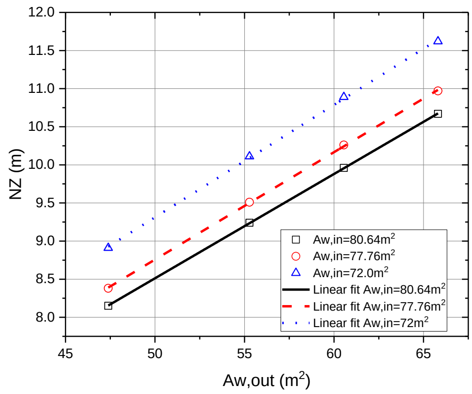

Figure 6. Height of the neutral zone from ground in the function of the exhaust air outlets aerodynamic area.

Figure 7 shows how the temperature under the roof of the building changes depending on the outside temperature for two cases of the active surface of the air intake/exhaust, respectively: 1) 77.76 m^2/71.08 m^2as well as 2) 106.56 m^2/76.34 m^2.

The upper straight line in Figure 7 shows how the temperature under the roof of the building varies with changes in weather conditions and for all opened air supply and exhaust openings with a total active area of 77.76 and 71.08 m^2, respectively (27+27 air intakes and 27 exhaust vents); the areas have been set to meet the minimum requirements in Table 2 assuming that the design outside temperature is θ_e=30°C. On the other hand, the lower straight line concerns the fulfillment of the minimum requirements in the case of exceeding the design temperature by $\Delta\theta_e$=6K (38+36 inlets and 29 outlets).

Ventilation system devices, both supply and exhaust, can be provided with appropriate sensors and controllers. This enables the amount of supply and exhaust air to be regulated by opening or closing the active ventilation surfaces so that the temperature under the roof of the building is similar throughout the year. Therefore, the next stage of the simulation consists of indicating the optimal opening area for winter period, in which the design outside temperature for Kielce is θ_e=-20°C [24], and the heat losses amount to Φ_L=450kW. After closing the lower lane of the intakes (0 openings/27 all) and reducing the intake openings on the higher level (20 open/27 all) and the exhaust vents to 7 open/27 all, the temperature under the roof is 54.4°C, and the pressure equalization zone is located at the level of NZ = 9.34 m (see Figure 8); the supply velocity has not been exceeded and is v_{in} = 1.4 m/s.

What must also be analyzed is the impact of mechanical devices on natural convection in a model glasswork. In the Ventos software, in the 'Mechanical and hybrid ventilation devices' section, fans, air supply units and hybrid ventilation devices can be chosen. In our case, it is assumed that an exhaust fan with an output of 30,000 m^3/h is placed at the same height as the roof vents, that is, 22 m. For each of the three outside air temperatures analyzed above (i_e= +30, +36, -20 °C) and the optimal configuration of the natural ventilation systems of the supply and the exhaust, the influence of the presence of a mechanical device was checked. It is a classic case of hybrid ventilation, where the gravity installation is supported by an exhaust fan. Table 4 shows the results of this analysis.

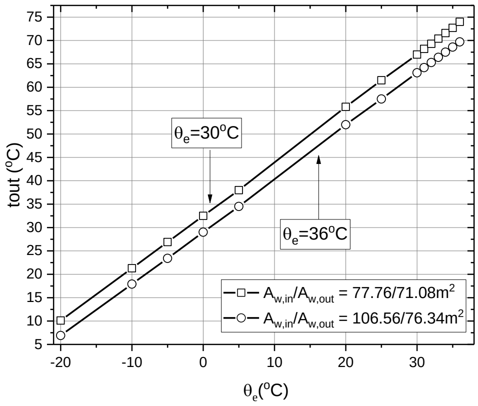

Figure 7. The temperature under the roof of the glassworks structure depends on the changing of external conditions, $t_{out}(\theta_e)$.

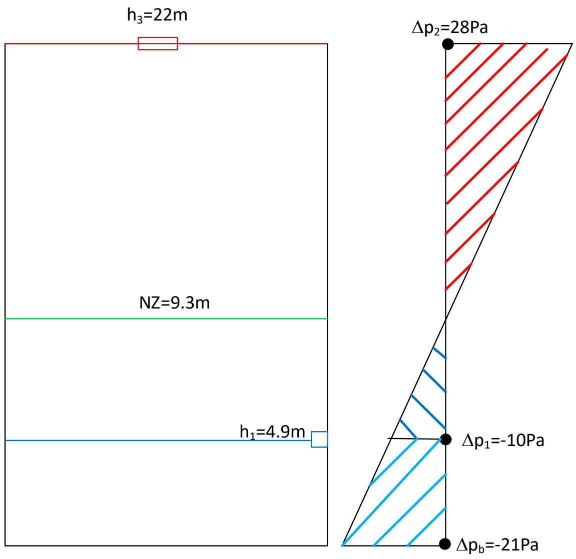

Figure 8. Height of the neutral zone from ground/pressure equalization zone, NZ for winter time.

Table 4. Results of computer simulation of the hybrid ventilation system in the glassworks for external temperatures of +30, +36 and -20°C, respectively.

Case no.	1	2	3	4	5	6	7	8
θ_e, °C	+30				+36		-20	
Ventilation system	natural	hybrid			natural	hybrid	natural	hybrid
Opened for incoming air (aerodynamic) $A_{w,in}$, m^2	77.76				106.56			28.80
Opened for outgoing air (aerodynamic) $A_{w,out}$, m^2	71.08			0	76.34	0		0
Incoming natural volumetric flow of air, V_{in}, m^3/h	933,347	976,577	973,098	875,790	1,047,074	1,093,690	372,895	331,954
Outgoing natural volumetric flow of air, V_{out}, m^3/h	1,048,959	970,560	977,094	-	1,159,868	-	482,514	-
Exhaust fun of volumetric flow of air, V_{out_FUN}, m^3/h	-	120,000	110,000	9x110,000	-	11x110,000	-	4x110,000
Temperature under top, t_{out}, °C	67.1	65.5	65.6	69.5	69.7	68.2	54.4	63.6
Height of the neutral zone from ground NZ, m	11.63	12.71	12.62	10.33	9.65	10.44	9.34	8.14

In the first case, the outgoing volumetric flow of air V_{out} is slightly higher than that of V_{in}, which is normal due to differences in the air density in the supply and exhaust air. If we add an extraction device in the form of a roof fan with an output of 120,000 m^3/h to this system, with gravity intake and exhaust vents, then $V_{out}<V_{in}$. This means that some of the air that should leave the building through the gravity vents is sucked in by the exhaust fan, which in this situation turns out to be ineffective (case no. 2). Only by reducing the efficiency of the mechanical device to 110,000 m^3/h are the appropriate values of the air stream drawn from the building (case no. 3). If we wanted to completely replace the gravity ventilators with mechanical fans (case no. 4), their capacity would have to be 9 x 110,000 m^3/h, which would ensure the correct temperature on the glassworks roof (69.5 <70^{o}C), and the pressure equalization zone would be at a reasonable level of 10.33 m. However, such a solution is much more expensive and does not ensure the maintenance of the design conditions for an outside temperature of + 36 °C (case no. 5). In this case, 11 exhaust fans are required (case no. 6).

In winter conditions, four fans are enough, but their presence lowers the pressure equalization zone to 8.14 m (cases 7 and 8).

These analyses and simulations confirm the accuracy and efficiency of using natural ventilation in facilities with significant heat gains, certainly include glassworks.

5. Conclusions

The paper concerns the optimization of natural ventilation in a model glassworks located in Kielce, where the total internal heat gains were determined as Φ_G = 11,200 kW. The calculations were made using the Ventos software [26]. The basic conclusions of the analysis carried out are as follows:

- determining the maximum temperature of the ventilation air under the roof of the building is of key importance for the safety of the structure; here t_{out}=70^{o}C,
- at the outdoor temperature, for the summer period, amounting to θe=30^{o}C, the most optimal solution ensuring the minimum internal temperature and air velocity conditions for the glassworks building is the use of wall inlets located on two levels, 27 on each and 27 air exhausts on the roof of the building; the pressure equalization zone is NZ = 11.63 m and is located more or less in the middle of the room height; limiting the active surface of the air inlets $A_{w,in}$ shifts the pressure stabilization point towards higher values, which is an unfavorable phenomenon - reducing the $A_{w,in}$ area by half results in an increase of NZ to a value of over 17 m,
- if the outside temperature increased by 6K, the area of intakes, $A_{w,in}$ should be increased by about 44%, and the $A_{w,out}$ outlet by 7%; only in this way the temperature under the ceiling t_{out} will not exceed the assumed value of 70^{o}C,
- in winter conditions, for the design outside temperature of θe=-20^{o}C, only 20 wall intakes on the upper level and 7 vents should be open; it ensures that the temperature under the roof of the building is kept at a similar level all year round,
- supply and exhaust elements should be mechanically controlled, depending on weather conditions,
- analyses and simulations made for hybrid ventilation confirm the accuracy and efficiency of using natural ventilation in facilities with significant heat gains, certainly include glassworks.

References

[1] Y. Wang, L. Cao, Y. Huang, Y. Cao,"Lateral ventilation performance for removal of pulsating buoyant jet under the influence of high-temperature plume". IndoorBuilding Environment, Vol. 29, 2020, 543–557.

[2] P. Wouters, N. Heijmans, C. Delmotte, L. Vandaele,"Classifiaction of hybrid ventilation concepts". Proceedings of the 21st AIVC Conference, Den Haag, 2000.

[3] V. Soebiyan, "The trend of hybrid ventilation systems". 4th International Conference on Eco Engineering Development, 2020, IOP Conf. Series: Earth and Environmental Science Vol. 794, 2021, 012178.

[4] G. Cao, H. Awbi, R. Yao, Y. Fan, K. Sir´en, R. Kosonen, J. Jensen, Zhang, "A review of the performance of different ventilation and airflow distribution systems in buildings", Building Environment, Vol. 73, 2014, 171–186.

[5] L. K. Moeya, M. F. Kongb, V. C. Taia, T. F. Goc, N. M. Adam,"Effect of Gable Roof Angle on Natural Ventilation for an Isolated Building".Jordan Journal of Mechanical and Industrial Engineering, Vol. 15, No. 3, 2021, 291 – 300.

[6] L. L. Gomis, M. Fiorentini, D. Daly,"Potential and practical management of hybrid ventilation in buildings". Energy & Buildings, Vol 231, 2021, 110597.

[7] V. Soebiyan, "Hybrid ventilation systems on different climate". 4th International Conference on Eco Engineering Development 2020, IOP Conf. Series: Earth and Environmental Science Vol. 794, 2021, 012174.

[8] M. Pinto, V. Peixoto de Freitas, J. C. Viegas, L. Matias,"Residential Hybrid Ventilation Systems in Portugal: Experimental Characterization". Conference Paper, June 2006.

[9] Y. Lim, H. Yun, D. Song,"Indoor Environment Control and Energy Saving Performance of Hybrid Ventilation System for a Multi-residential Building". Energy Procedia, Vol. 78, 2015, 2863 – 2868.

[10] Borodiņecs, A. Krēsliņš, E. Dzelzītis, A. Krūmiņš, "Introduction of hybrid ventilation systems of dwelling buildings in Latvia".Proceedings of the Sixth International conference on indoor air quality, ventilation and energy conservation in buildings: sustainable built environment, Sendai, Japan, 2007.

[11] H. Davidsson, L. R. Bernardo, S.Larsson,"Design and Performance of a Hybrid Ventilation System with Heat Recovery for Low Energy Buildings". Journal of Environment and Engineering, 2011, Vol. 6, No. 2,469-477.

[12] R. Al-Rbaihat, A. Sakhriehb, J. Al-Asfar, A. Alahmer, O. Ayadi, A. Al-Salaymeh, Z.Al_hamamre, A. Al-bawwab, M. Hamdan,"Performance Assessment and Theoretical Simulation of Adsorption Refrigeration System Driven by Flat Plate Solar Collector". Jordan Journal of Mechanical and Industrial Engineering, Vol. 11, No. 1, 2017, 1 -11.

[13] S. Yoon, J. Seo, J. Lee, D. Song. A,"Study on Design Method for Hybrid Ventilation System in High-rise Residential Buildings". Conference Paper, May 2010.

[14] C.Vornanen-Winqvist, H.Salonen, Kati Järvi, M.A. Andersson, R.Mikkola, T.Marik, L. Kredics, J.Kurnitski, "Effects of Ventilation Improvement on Measured and Perceived Indoor Air Quality in a School Building with a Hybrid Ventilation System". International Journal of

Environmental Research and Public Health, Vol. 15, No. 7, 2018, 1414.

[15] E.Ramez, F. Habib,"Providing Design Strategies for Ventilation System in Treatment Environments (Proposed Sample: Hybrid Ventilation System in Hospitals)". International Journal of Architecture and Urban Development, Vol. 8, No.4, 2018, 1-4.

[16] X.Fua, D. Wu,"Comparison of the efficiency of building hybrid ventilation systems with different thermal comfort models". Energy Procedia, Vol. 78, 2015, 2820 – 2825, 6th International Building Physics Conference, IBPC 2015.

[17] X. Dou, D.Xie, Z. Wang, P. Xiao, H. Wang,"Improved buoyancy-driver hybrid ventilation system for multiple-heat-source industrial buildings. Case Studies". Thermal Engineering, Vol. 26, 2021, 101059.

[18] H. Davidsson, R. Bernardo, B.Hellström,"Theoretical and Experimental Investigation of a Heat Exchanger Suitable for a Hybrid Ventilation System". Buildings Vol. 3, 2013, 18-38.

[19] J. Zhang, F.Haghighat,"Simulation of earth-to-air heat exchangers in hybrid ventilation systems". Ninth International IBPSA Conference Montréal, Canada, 2005.

[20] W. Turner, H.Awbi,"Hybrid ventilation for cooling application".Conference paper, IAVEC 2007.

[21] R. Chatys, Ł. J. Orman, "Technology and properties of layered composites as coatings for heat transfer enhancement". Mechanics of Composite Materials, Vol. 53, No. 3, 351-360.

[22] W. J. N.Turnera,, H. B. Awbi, T. Payne,"Solar-driven hybrid ventilation system".The 9th World Renewable Energy Congress, Florence, Italy, 2006.

[23] Kontrymowicz, Ventosystem Natural ventilation in a glassworks - can it be controlled?,Cyrkulacje Vol. 20,2014, 45-47, www.cyrkulacje.pl

[24] W. Wciślik, R.Pała,"Some Microstructural Aspects of Ductile Fracture of Metals". Materials, Vol. 15, No 15, 2021, 4321.

[25] PN-B-03420:1976: Ventilation and air conditioning - Calculation parameters of the outside air.

[26] The VENTOS to calculate natural ventilation Copyright © 2022 VENTOSYSTEM Bohdan Kontrymowicz, www.ventosystem.pl

[27] www.meteoblue.com (access:14.02.2022).\