Increasing energy efficiency and resource saving thanks to the design solution on the use of reversible jet ventilation system for four-storied underground garage in national cultural center of Kazan

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Abstract. In modern metropolitan cities, mass construction of multi-storied underground and closed-type above-ground garages of quite large areas with quite low ceilings (up to 3.5 – 2.5 m) is observed, which requires new approaches to the selection of the ventilation arrangement and its main technical characteristics. Jet ventilation systems have found extensive use. In 2018 in Kazan, an underground four-storied garage equipped with reversible jet ventilation and smoke extraction system (the first in Russia) was constructed and handed over to the customer. Taking into account the absence of any experience in Russia in the field of design and construction of jet ventilation systems, a comparative analysis of traditional duct ventilation systems and jet ventilation systems of closed (underground) car-parking spaces widely used all over the world has been performed. The choice of reversible jet ventilation is justified keeping in mind the parameters of energy efficiency and underground space development effectiveness. In this work, we have performed a critical analysis of ventilation systems with regard exactly to these parameters. Besides, we have shown the advantage of reversible jet ventilation in terms of ensuring safe evacuation of people in the case of fire. For the first time, we propose a scientifically grounded method of calculation of longitudinal jet ventilation and smoke removal system of the parking lot. As a result, design rules have been developed to ensure human safety in case of fire and energy efficiency in normal operation of the jet ventilation system.

1. Introduction
The use of jet ventilation systems in modern underground and closed car-parking spaces has a number of advantages in comparison with traditional duct ventilation systems. The article performs the analysis of specific features of jet ventilation systems through the example of the first in Russia four-storied underground garage built in Kazan in 2018 and equipped with reversible jet ventilation [1]. It is shown that this technical solution has permitted to improve a whole range of parameters:

- to increase safety while evacuating people in an emergency situation in case of fire;
- to cut down ecological risks and improve the conditions of stay for people in the parking area in the regular operation mode;
- to use more effectively the underground space;
- to increase the energy efficiency of the ventilation system.
The main obstacle to the use of such ventilation systems was the lack of scientifically sound calculation methodology and relevant regulatory document.

The purpose of this article is to present the results of the research, which allow the development of a normative document [2], to make a choice of optimal parameters of the system of jet ventilation of a car parking lot and to achieve high indicators of efficiency in practice.

2. Analysis of use of ventilation systems in the underground car-parking spaces

The use of traditional duct ventilation systems has become problematic due to a number of reasons, namely:

- large areas of fire compartments have demanded to increase the design fire load, to increase the required productivity of smoke extraction fans and, hence, to increase the height of the ceilings in order to accommodate the smoke extraction system ducts [2, 3];
- an increase in the length of plenum and exhaust ventilation ducts as a result means an increase in expenses for the construction and servicing the ventilation systems and losses associated with aerodynamic resistances and air leaks in air ducting.

With low ceilings, the organization of smoke extraction in case of fire in the garage has some peculiarities described in publications [2, 4, 5]. The duct ventilation envisages transverse smoke extraction (from bottom to top) with the formation of a thin layer of smoke in the under-ceiling space. Such design taking into consideration the non-stationary car fire mode and low ceilings is rather too risky. When a longitudinal jet ventilation is used (the ventilation flow is directed horizontally) the height of the ceiling may not be considered a risk factor. The research of the mechanism of movement of hot smoke gases and cold supply air with the longitudinal smoke removal scheme has been performed on the basis of the model using the Froude number, as shown in [6, 7].

In Russia, the refusal to use jet ventilation systems in car-parking spaces has been stipulated by regulatory reasons. Not the least of the factors were low effectiveness requirements to smoke extraction fans. An important factor was low requirements to effectiveness of smoke exhaust fans. As distinguished from the European design rules, the Russian normative documents permit minimum smoke extraction productivity to be 1.5 – 2 times less which is shown in [8]. Hence, the problem of the size of smoke extraction system ducts was not so critical.

Following the development of the domestic normative document [2] establishing the rules of design, installation and commissioning to the customer of jet ventilation systems for car-parking spaces, this regulatory interdiction was removed.

3. Peculiarities of jet ventilation design and operation

The jet ventilation system of a car parking lot, as a rule, has a dual function that provides normal regular (general exchange) and emergency (smoke removal in case of fire) operating modes. The power consumption in the normal mode does not usually exceed 25% of power consumption in the emergency mode. Therefore, it is the fire parameters envisaged in the project that determine the composition of the jet ventilation system equipment.

The method of calculation proposed below allows choosing parameters of the jet ventilation system to ensure safe and comfortable stay of people in an underground parking lot with minimal energy consumption of the ventilation system. When calculating the parameters of the jet ventilation system, it is necessary to determine:

- minimum allowable air exchange in normal and emergency modes, standard size of plenum and exhaust fans (smoke exhaust);
- standard size and number of jet fans.

Figure 1 shows the scheme of flue gas distribution in case of a car fire in the parking lot equipped with longitudinal jet smoke exhaust system. The ventilation system creates different-density and different-velocity flows, namely, a high-velocity flow of hot flue gases in the sub-ceiling space and a low-velocity flow of cold air supply.
Figure 1. Scheme of different-density flows of air and flue gases providing protection for people and prevention of smoke concentration in the evacuation exits during operation of jet ventilation:

1—outflow; 2—conditional separation boundary of different-density air flows; 3—inflow; 4—calculated boundary of smoke.

In papers [4–7], it is shown that the condition of safe evacuation of people in case of fire is the provision of the lower boundary of smoke at a height $Y$; the latter may be achieved by providing different density of the hot layer of flue gases and cold air supply below line 2. The considered effect of flue gas buoyancy is possible with the value of Froude number ($Fr$) presented in formula (1) of not more than 4.5.

$$Fr = \frac{9.8Y(T_m - T_0)}{T_m V_1}$$  \tag{1}

where $T_m$ is the temperature of the gas-air mixture behind the seat of fire, K; $T_0$ is the plenum air temperature, K; $V_1$ is the plenum air velocity before the seat of fire, m/s.

The value of speed $V_1$ corresponding to the maximum permissible value $Fr = 4.5$ is called the critical speed $V_{1cs}$.

$$V_{1cs} = \sqrt[3]{\frac{M}{2} + \sqrt[3]{\frac{M^2}{4} + \frac{L}{27}} + \sqrt[3]{\frac{M}{2} - \sqrt[3]{\frac{M^2}{4} + \frac{L}{27}} - \frac{D}{3}}}$$  \tag{2}

where

$$L = -\frac{D^3}{3}, \quad M = D\left(\frac{2D^3 - A}{27}\right), \quad D = \frac{Q_v}{(t_0 + 273)\rho_cr BY}, \quad A = \frac{9.8Y}{Fr}$$  \tag{3}

$B$ is the width of the car parking lot smoke localization zone, m; it may be assumed equal to the parking lot overall dimension perpendicular to the flue gas flow (see figure 1); $Q_v$ is the convective power of fire, kW.

The efficiency of the smoke ventilation system corresponding to the value of $V_{1cs}$ is shown on the graph presented in figure 2.
Figure 2. Graph of dependence of smoke exhaust fan capacities $V_{ex}$ on the parking lot width $B$ at different values of convective fire power magnitudes $Q_c$, at $Y = 2$ m and $Fr = 4.5$:

1—outflow; 2—conditional separation boundary of different-density air flows; 3—inflow; 4—calculated boundary of smoke.

Thus, with due account of the project data, the capacity and power of the inflow and exhaust (smoke extraction) fans are determined.

Figure 3 shows the installation layout of the jet fans under the ceiling of the car parking lot, where the maximum allowable distance between the fans $L_n$ is selected from the condition:

$$v_{x \min} \geq V_{lez},$$

where $v_{x \min}$ is the minimum axial velocity of an axially symmetrical flooded air jet generated by an axial jet fan, m/s.

Figure 3. Installation of jet fans under the ceiling of the car parking lot.

In accordance with the relationships obtained in the papers [12, 13], the maximum areas of the parking lots $S_{vl}$ ventilated by a single jet fan depending on its axial design reactive draught $F_p$ at different values of $v_{x \min}$ were calculated. The results of these calculations are shown in figure 4.
Figure 4. Graph of dependence of the area $S_{\text{v1}}$ ventilated by one fan on the calculated reactive draught of the fan $F_p$ at different values of $v_{\text{min}}$.

The jet fan standard size is selected taking into account the ceiling and vehicle height values. With the help of the graph in figure 4, the minimum number of jet fans for a given room is determined.

The above mentioned method of calculation of the jet ventilation and smoke removal system allowed the selection of ventilation equipment for the underground four-storied car parking lot in Kazan.

In the underground space of the car parking lot in Kazan it was possible to accommodate 4 floors instead of 3 floors provided by the original project. The designed number of parking spaces was increased by 28%.

An important feature of jet ventilation is a noticeable reduction in energy consumption as compared to the similar duct systems.

The share of energy consumption for air conditioning and ventilation in the energy balance of industrial and public buildings can reach, depending on the purpose and time of year, very significant values from 25 to 50%. For closed underground and covered parking lots, this figure can be even higher and reach 60% [10, 11].

Table 1 shows the average daily energy consumption of the ventilation systems of the parking lot of 4000 m$^2$, equipped in one case with a traditional duct system, and in the other with a jet ventilation system.

| Ventilation system operation mode | Duct ventilation system, kW h | Plenum and exhaust fans, kW h | Jet fans, kW h | Total load, kW h |
|----------------------------------|-------------------------------|------------------------------|---------------|-----------------|
| Round-the-clock operation with an interruption for 7 hours at night | 189.6 | 121.9 | 40.8 | 162.7 |
| Operation with the use of a timer | 110.6 | 71.1 | 23.8 | 94.9 |
| Operation on CO sensor signal with continuous operation of plenum ventilation | 51.2 | 33.1 | 6.8 | 39.9 |
| Operation on CO sensor signal without continuous operation of plenum ventilation | 31.6 | 20.3 | 6.8 | 27.1 |

Table 1. Average daily energy consumption of ventilation systems in the parking lot.
The advantage of jet ventilation as it pertains to energy efficiency may be explained by the absence of aerodynamic losses and air leaks so characteristic of traditional duct ventilation, which is caused by air movement through air ducts.

The comparative evaluation of various designs shows that jet ventilation exceeds the traditional duct ventilation in terms of energy efficiency in all considered modes of operation approximately by 15%.

4. Findings
The use of the proposed method of calculation of the jet ventilation and smoke exhaust system allowed:

a) choosing the parameters of the jet ventilation system;

b) minimizing energy consumption of the ventilation system;

c) demonstrating that the jet ventilation systems of car parking lots have a number of advantages in comparison with the traditional duct ventilation:

• absence of air ducts;

• decrease in ceiling height and increase of underground space use effectiveness (thanks to more dense component configuration);

• increasing energy efficiency and reducing operation costs (on account of lack of pressure loss and air leaks from air ducting), exclusion of expenses for periodic cleaning of air ducts.

5. Conclusion
The new methodology of calculation of the reversible jet ventilation system proposed by us can be recommended for the use in designing underground car parking lots.

This technique has been successfully tested on the example of calculation of the reverse jet ventilation system of an underground car parking lot in Kazan. The application of this technique allowed an increase in energy efficiency of the ventilation system and more effective use of the developed underground space.

References
[1] Volkov A P and Sverdlov A V 2015 AVOK Ventilation. Heating. Air conditioning 1 34–8
[2] Vishnevsky E P and Volkov A P 2012 Mir stroitelstva i nedvizhimosti 45 43–44
[3] Sverdlov A V, Volkov A P, Rykov S V, Klimovich M V and Volkov M A 2016 Scientific journal NIU ITMO. Series: Refrigeration engineering and air conditioning 4 23–32
[4] Senveli A, Dizman T, Celen A, Bilge D, Dalkılıç A S and Wongwises S 2015 J. Therm. Eng. (Istanbul, Turk.) 1 116–30
[5] Sverdlov A V, Volkov A P, Rykov S V, Volkov M A and Barafanova E Yu 2019 Journal of IAR 1 3–10
[6] Sverdlov A V, Volkov A P, Rykov S V, Gordeeva E A and Volkov M A 2018 Scientific journal NIU ITMO. Series: Refrigeration engineering and air conditioning 1 47–56
[7] Sverdlov A V and Volkov A P 2017 AVOK Ventilation. Heating. Air conditioning 6 34–7
[8] Sharipov A Ya, Grimitlin A M, Volkov A P and Sverdlov A V 2018 SP 300.1325800.2017 System of jet ventilation of underground and covered parkings. Rules of Design (Moscow: Standarty) 57
[9] Sverdlov A V and Volkov A P 2018 Engineering systems 4 20–2
[10] Volkov A P, Sverdlov A V, Rykov S V and Volkov M A 2015 Scientific journal NIU ITMO. Series: Refrigeration engineering and air conditioning 3 28–36
[11] Vishnevsky E P 2004 S.H.A. Sanitary ware, Heating, Air conditioning 11 90–101