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EMERGENCY VENTILATION OF CLEAN ROOMS

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Statement of the problem. In modern industry, clean room technology is commonly used to monitor the state of the air. The use of toxic gases in clean rooms might result in emergencies that call for emergency ventilation. In order to calculate the emergency air exchange, it is necessary to design a model of emergency air exchange considering a significant number of influencing factors.
Results. The model of emergency air exchange for a clean room is developed based on the equation of material balance on the harmful gas allocated from the equipment in case of an emergency. The solution of the model of the emergency air exchange for a clean room is obtained allowing the concentrations of harmful gas to be calculated depending on a specific emergency. The properties of the resulting solution are investigated. The concept of accumulating capacity of the ventilated room is introduced and the influence of accumulating capacity on change of concentrations of harmful gas is evaluated.
Conclusions. The performed calculations allow one to understand the processes of development of an emergency situation in a clean room more profoundly and to allow for these risks while designing emergency ventilation of clean rooms.

Keywords: clean rooms, emergency ventilation, emergency, storage capacity of the ventilated room, concentration of harmful gas.

Introduction. Clean rooms are used in industry to stipulate strict control of the state of the air environment (i.e., the amount of dust particles in the air, temperature, humidity, etc.). Cleanrooms are used in production of electronic components such as integrated circuits and hard drives; in the field of biotechnology and medicine, clean rooms are employed when it is essential to provide the air environment free from bacteria, viruses or other pathogens [6, 12, 13, 19, 24].

Cleanrooms are particularly designed as controlled enclosed spaces where the parameters of the air environment are maintained within specified limits. The general requirements for clean rooms are formulated in ISO 14644. The design of clean rooms is much more diverse than traditional temperature and humidity control, and must take into consideration multiple requirements of the technological equipment. Thus, manufacturing of electronic components can be accompanied by the release of a large amount of potentially harmful vapors and gases [9, 15, 18, 21, 22]. In production of electronic components using the epitaxial growth technology, toxic gases such as arsine (AsH3) and phosphine (PH3) can be utilized as dopants. Exposure to these harmful gases might cause long-term health problems for staff members [4, 10, 16, 17, 20, 23].

Employers might also be subjected to regulatory sanctions. Under these conditions, an important task is to identify the required emergency air exchange when harmful gases escape from the equipment into a free volume of the room.

1. Mathematical model of emergency air exchange. For the calculated emergency, the release of harmful gases from the equipment under pressure will be considered. As a model of emergency air exchange for a clean room, the differential equation of the material balance for the harmful gas released from the equipment in the event of an emergency are used [2, 3, 11, 14]:

$$G d\tau - L c d\tau = V dc, \quad (1)$$

where G is the rate of release of harmful gas from the equipment in the event of an emergency into the volume of the clean room, kg·sec^{-1}; τ is the time, sec; L is the amount of air removed from a clean room, m^3·sec^{-1}; c is the gas concentration in a clean room, kg·m^{-3}; V is the volume of a clean room, m^3.

The equation (1) can be transformed as follows:

$$\frac{dc}{d\tau} + kc - \frac{G}{V} = 0, \quad (2)$$

where k is the frequency of air exchange in a clean room , sec^{-1}.

The initial conditions for solving the ordinary differential equation (2) will be the concentration of harmful gas at the initial moment of time. Let us consider the most unfavorable case of isothermal gas expansion in the equipment, then the consumption of harmful gas during its outflow from the equipment is given by the dependence [1, 5, 7, 8]:

$$G = G_0 e^{-a\tau}, \quad (3)$$

where the initial gas flow rate G_0 and the coefficient a are given by the formulas:

$$G_0 = FP_0\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}\sqrt{\frac{\mu}{RT}},$$

$$a = \frac{F}{V_{об}}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\sqrt{\frac{RT}{\mu}},$$

where F is the area of the hole through which the harmful gas flows out, m^2; P_0 is the initial pressure in the equipment, Pa; V_{vol} is the volume of equipment filled with gas, m^3; γ is the gas adiabatic index; R is the universal gas constant, J·deg^{-1}·kmol^{-1}; T is the gas temperature in the equipment, K; μ is the weight of a kilomole of gas, kg·kmol^{-1}.

2. Results of calculations using the emergency air exchange model for a clean room. Substituting (3) into (2), we get:

$$\frac{dc}{d\tau} + kc - \frac{G_0}{V}e^{-a\tau} = 0. \quad (4)$$

Solving (4) under the initial conditions $\tau = 0$, $c = 0$, we get:

$$c = \frac{G_0}{L}\frac{k}{k-a}\left(e^{-a\tau} - e^{-k\tau}\right). \quad (5)$$

Expression (5) describes the change in the concentration of harmful gas in the volume of the clean room depending on the properties of the harmful gas, the parameters of the outflow of the harmful gas and the parameters of emergency ventilation.

The graph of the change in the concentration of harmful gas in the volume of the clean room calculated by the formula (5) is shown in Fig. 1. The concentration of harmful gas increases from 0 to its maximum value, and then goes up and asymptotically approaches 0.

Let $V \to 0$, expression (5) is transformed as follows:

$$c = \frac{G_0}{L}e^{-a\tau}. \quad (6)$$

A change in gas concentrations in the volume of the clean room,calculated using formula (6) is shown in Fig. 1.

The important parameters of emergency ventilation are the value of the maximum concentration of the harmful gas and the time to reach the value of the maximum concentration of the harmful gas. Let us examine the concentration of harmful gas in the volume of the clean room (5) to the maximum:

$$\frac{dc}{d\tau} = 0.$$

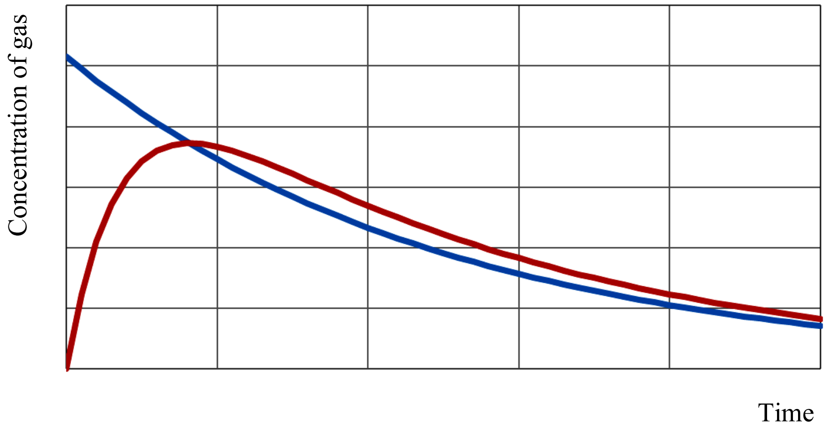

Fig. 1. Changes in the concentration of harmful gas in the volume of the clean room:
— is a change in gas concentrations in the volume of a clean room according to the formula (5);
— is a change in gas concentrations in the volume of the clean room at $V \to 0$ according to the formula (6)

Then

$$ae^{-a\tau} = ke^{-k\tau},$$

by tranforming we get

$$\tau_{max} = \frac{1}{a-k} \ln \frac{a}{k}. \tag{7}$$

Inserting (7) into (5), we get:

$$c_{max} = \frac{G_0}{L} \frac{k}{k-a} \left(\left(\frac{a}{k} \right)^{\frac{a}{k-a}} - \left(\frac{a}{k} \right)^{\frac{k}{k-a}} \right). \tag{8}$$

The intersection of the graphs of functions (5) and (6) occurs at the maximum point of function (5):

$$\frac{k}{k-a} \left(e^{-a\tau} - e^{-k\tau} \right) = e^{-a\tau},$$

hence

$$\tau = \frac{1}{a-k} \ln \frac{a}{k} = \tau_{max}.$$

Fig. 2 shows two graphs of changes in the concentration of harmful gas in the volume of the cleanroom calculated using the dependencies (5) and (6). They intersect at the point of maximum concentration of harmful gas with the coordinates (τ_{max}, c_{max}).

The analysis of Fig. 2 shows that the ventilated room until the moment of time τ_{max} accumulates in its volume a certain amount of gases, and then gives them away. Let us define the storage capacity of the ventilated room.

Fig. 2. Storage capacity of the clean room:
is the gas accumulation area; is the gas release area

Area 1 in Fig. 2 multiplied by L is the storage capacity of the clean room. Area 2 in Fig. 2 multiplied by L is the mass of the released gas.

Let us calculate the mass of the accumulated gas:

$$m = S_1 L = G_0 \int_0^{\tau_{\max}} e^{-a\tau} d\tau - G_0 \frac{k}{k-a} \int_0^{\tau_{\max}} \left(e^{-a\tau} - e^{-k\tau}\right) d\tau =$$

$$= G_0 \left(-\frac{1}{a}\right) e^{-a\tau} \Bigg|_0^{\frac{1}{a-k}\ln\frac{a}{k}} - G_0 \frac{k}{k-a} \left(\left(-\frac{1}{a}\right) e^{-a\tau} \Bigg|_0^{\frac{1}{a-k}\ln\frac{a}{k}} + \frac{1}{k} e^{-k\tau} \Bigg|_0^{\frac{1}{a-k}\ln\frac{a}{k}} \right) =$$

$$= G_0 \frac{1}{a} \left(1 - \left(\frac{a}{k}\right)^{\frac{a}{k-a}} \right) - G_0 \frac{k}{k-a} \left(\frac{1}{a} \left(1 - \left(\frac{a}{k}\right)^{\frac{a}{k-a}} \right) \right) - \frac{1}{k} \left(1 - \left(\frac{a}{k}\right)^{\frac{k}{k-a}} \right) = G_0 \frac{1}{k-a} \left(\left(\frac{a}{k}\right)^{\frac{a}{k-a}} - \left(\frac{a}{k}\right)^{\frac{k}{k-a}} \right).$$

The mass of the released gas is

$$S_2 L = G_0 \frac{k}{k-a} \left(-\frac{1}{a} e^{-a\tau} \Bigg|_{\frac{1}{a-k}\ln\frac{a}{k}}^{\infty} + \frac{1}{k} e^{-k\tau} \Bigg|_{\frac{1}{a-k}\ln\frac{a}{k}}^{\infty} \right) - G_0 \left(-\frac{1}{a}\right) e^{-a\tau} \Bigg|_{\frac{1}{a-k}\ln\frac{a}{k}}^{\infty} =$$

$$= G_0 \frac{1}{k-a} \left(\left(\frac{a}{k}\right)^{\frac{a}{k-a}} - \left(\frac{a}{k}\right)^{\frac{k}{k-a}} \right).$$

In line with the expectations, the amount of the accumulated gas is equal to the amount of gas discharged.

3. Storage capacity of the volume of the ventilated room when harmful gas enters it from the equipment under pressure will be:

$$m = G_0 \frac{1}{k-a}\left(\left(\frac{a}{k}\right)^{\frac{a}{k-a}} - \left(\frac{a}{k}\right)^{\frac{k}{k-a}}\right). \quad (9)$$

The ability of the volume of the ventilated room to accumulate harmful gas reduces the maximum concentration cmax and increases the time it takes to reach τ_{max}.

Conclusions. Clean room technologies are currently frequently used in various industries to ensure the required parameters of the air environment. In clean rooms, emergency ventilation must be provided as technological processes can use toxic gases.

Based on the differential equation of material balance for harmful gas, a model of emergency air exchange for a clean room has been developed. For a calculated emergency, the release of harmful gases from the equipment under pressure is accepted.

The solution is obtained in the elementary functions of the emergency air exchange model for a clean room. Therefore a new concept of the accumulating capacity of a ventilated room has been introduced. An increase in the storage capacity of a ventilated room causes a decrease in the maximum concentration of harmful substances from the equipment under pressure.

The use of the concept of the accumulating capacity of a ventilated room will simplify the calculations of general exchange and emergency ventilation for rooms with non-stationary sources of hazardous substances.

The results shed more light on the development of an emergency in a clean room and enable one to calculate the parameters of emergency ventilation in clean rooms.

References

1. Mel'kumov V. N., Kuznetsov S. N., Gulak V. V. Modelirovanie zadymlennosti pomeshchenii slozhnoi konfiguratsii v nachal'noi stadii pozhara [Modeling of the smoke content of rooms of complex configuration in the initial stage of a fire]. *Nauchnyi vestnik VGASU. Stroitel'stvo i arkhitektura*, 2010, no. 3 (19), pp. 131—139.

2. Mel'kumov V. N., Kuznetsov S. N., Pavlyukov S. P., Cheremisin A. V. Nestatsionarnoe pole kontsentratsii prirodnogo gaza v skvazhine pri ego utechke iz podzemnogo gazoprovoda [Non-stationary field of natural gas concentrations in a well when it leaks from an underground gas pipeline]. *Privolzhskii nauchnyi zhurnal*, 2008, no. 4 (8), pp. 98—103.

3. Mel'kumov V. N., Kuznetsov S. N., Sklyarov K. A., Cheremisin A. V. Nestatsionarnye protsessy formirovaniya sistemami ventilyatsii vozdushnykh potokov v pomeshcheniyakh [Non-stationary processes of formation of air flows by ventilation systems in rooms]. *Izvestiya OrelGTU. Ser.: Stroitel'stvo. Transport*, 2007, no. 3—15 (537), pp. 36—39.

4. Mel'kumov V. N., Kuznetsov S. N., Lachugin I. G., Sviridov A. A. O metodike rascheta kontsentratsii prirodnogo gaza pri nalichii utechki iz podzemnogo gazoprovoda [On the methodology for calculating natural

gas concentrations in the presence of a leak from an underground gas pipeline]. *Vestnik VGTU, Ser.: Energetika*, 2001, vol. 7.1, pp. 72—75.

5. Polosin I. I., Derepasov A. V. Modelirovanie ventilyatsionnykh protsessov v proizvodstvennykh pomeshcheniyakh s proemami v mezhduetazhnykh perekrytiyakh [Modeling of ventilation processes in industrial premises with openings in floor-to-floor ceilings]. *Nauchnyi vestnik VGASU. Stroitel'stvo i arkhitektura*, 2011, no. 2 (22), pp. 43—51.

6. Polosin I. I., Lobanov D. V. Raschet trebuemogo vozdukhoobmena v ofisnom pomeshchenii pri organizatsii personal'noi sistemy ventilyatsii [Calculation of the required air exchange in an office space when organizing a personal ventilation system]. *Privolzhskii nauchnyi zhurnal*, 2014, no. 1 (29), pp. 56—60.

7. El'terman V. M. *Ventilyatsiya khimicheskikh proizvodstv* [Ventilation of chemical production facilities]. Moscow, Khimiya Publ., 1971. 238 p.

8. El'terman, V. M. Teoreticheskie i eksperimental'nye osnovy ventilyatsii proizvodstv s vydeleniem toksichnykh gazov i parov. Diss. d-ra tekh. nauk [Theoretical and experimental bases of industrial ventilation with the release of toxic gases and vapors. Dr. eng. sci. diss.]. Moscow, 1973. 314 p.

9. ANSI/ASHRAE Standard 62.2-2013. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. Atlanta, ASHRAE, 2013.

10. Beggs C. B., Sleigh P. A. A quantitative method for evaluating the germicidal effect of upper room UV fields. *Journal of Aerosol Science*, 2002, no. 33, pp. 1681—1699.

11. Dijkstra D., Loomans M. G., Hensen J. L. M., Cremers B. E. Ventilation efficiency in a low-energy dwelling setting — a parameter study for larger rooms. Proceedings of the 14th International Conference on Indoor Air Quality and Climate (Indoor Air — 2016), 2016, p. 8.

12. Fedotov A. Saving energy in cleanrooms. *Cleanroom Technol*, 2014, vol. 22, no. 8, pp. 14—18.

13. Khoo C. Y., Lee C. C., Hu S. C. An experimental study on the influences of air change rate and free area ratio of raised-floor on cleanroom particle concentrations. *Build. Environ*, 2012, no. 48 (1), pp. 84—88.

14. Kircher K., Shi X., Patil S., Zhang K. M. Cleanroom energy efficiency strategies: Modeling. *Energy Build*, 2010, vol. 42, no. 3, pp. 282—289.

15. Loomans M. G., Molenaar P. C. A., Kort H. S. M., Joosten P. H. J. Energy demand reduction in pharmaceutical cleanrooms through optimization of ventilation. *Energy Build*, 2019, 109346. Available at: https://doi.org/10.1016.

16. Molenaar P. Ventilation efficiency in pharmaceutical cleanrooms — Pilot study graduation. *Eindhoven University of Technology*, 2016.

17. Noakes C. J., Sleigh P. A. Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards. *J. R. Soc. Interface*, 2009, suppl. 6, pp. S791—S800.

18. Ogunsola O. T., Wang J., Song L. ASHRAE Research Project Report 1399-RP: Survey of particle production rates from process activities in pharmaceutical and biological cleanrooms. Oklahoma, 2018.

19. Reinmüller B. People as a Contamination Source — Clothing Systems. Dispersion and Risk Assessment of Airborne Contaminants in Pharmaceutical Cleanrooms. *Building Services Enginiring Bulletin*, 2001, no. 56, pp. 54—77.

20. Sun J. M. W., Flyzik K. Cleanroom pressurization strategy update-Quantification and validation of minimum pressure differentials for basic configurations and applications. *ASHRAE Trans*, 2013, part 1, p. 16.

21. Tschudi W., Faulkner D., Hebert A. Energy efficiency strategies for cleanrooms without compromising environmental conditions. *ASHRAE Transactions*, 2005, vol. 111, part 2, no. 2, pp. 637—645.
22. Villafruela J. M., Castro F., San Jose J. F., Saint-Martin J. Comparison of air change efficiency, contaminant removal effectiveness and infection risk as IAQ indices in isolation rooms. *Energy Build*, 2013, vol. 57, pp. 210—219.
23. Whyte W., Whyte W. M., Eaton T. The application of the ventilation equations to cleanrooms; Part 2: Decay of contamination. *Clean Air and Containment Review*, 2014, no. 20, pp. 4—9.
24. Xie X., Li Y., Chwang A. T., Ho P. L., Seto W. H. How far droplets can move in indoor environments-revisiting the Wells evaporation-falling curve. *Indoor Air*, 2007, jun., no. 17 (3), pp. 211—25.