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Theoretical Studies of the Influence of Crack Development on the Change in Air Permeability of Building Structures

Y A Vorob'eva[1], M N Zherlykina[1], E E Burak[1]

[1]Department of housing and communal services, Voronezh State Technical University Voronezh, 20-letiya Oktyabrya ,84, 394000 Russia,

E-mail: cccp38@yandex.ru

Abstract. The results of a theoretical study of the influence of crack development in the enclosing structures of residential buildings on their air permeability are presented. The mathematical model of infiltration of air through a crack passing in an arbitrary direction in the enclosing structure is considered in the article. The air motion for the reduced flow diagram of a continuous medium is described by the Navier-Stokes equations. The solution of the equation is obtained using the Galerkin method. With regard to thin layers of the air environment, assumptions are made that make it possible to compile a system of equations, including the equations of dynamics and the continuity equation. A solution is obtained that allows to determine the consumption characteristics of outdoor air passing through a through crack in the enclosing structure taking into account its linear dimensions and the excess pressure.

1. Introduction

The internal environment of residential and public buildings is formed with the help of restrictive structures and engineering equipment, which, during operation, undergo changes, as a rule, for the worse. There is a violation of the outer protective layer, cracks and faults are formed. The formation of a crack in the ogrezhdayuschey construction violates its uniformity, promotes the penetration of moisture and various substances from the outside air into the room, increases the mobility of the internal air, lowers the temperature field of the enclosure, and is one of the reasons for reducing the thermal efficiency of buildings with significant wear [1…5].

Investigation of the development of cracks during technical inspection of a building is necessary to determine the actual technical condition of the facility with the aim of making managerial decisions to improve the operational qualities of the building. It is important to study the parameters of cracks as verification values for determining the critical state of structures and their performance properties.

To ensure and regulate comfortable conditions in the premises, it is necessary to investigate the change in the properties of the enclosing structures during their aging and wear. For this, a mathematical model of air exchange through fences with various physical wear is needed. As basic models of many processes, boundary value problems for nonstationary convection-diffusion equations are second-order parabolic equations with lower terms [6]. Equations of motion, energy and continuity in combination with the initial and boundary conditions allow us to formulate a physico-mathematical formulation of the problem of the distribution of temperature, velocity, and concentration of substances in a room near enclosing structures subject to physical wear. To solve the equations, it is necessary to identify the conditions for their closure, which require the experimental establishment of the characteristics of these phenomena. At present, there are no common methods for identifying these characteristics, although the use of numerical, including variational methods, has become very popular in recent years.

Consider the wear of the outer wall in the form of a crack passing in an arbitrary direction. To investigate the effect of crack development on the air permeability of the fence, a design scheme [7,8] was drawn up, for which the following assumptions were made: a crack can be represented as a gap of size *r* filled with air; the linear dimensions of the surface formed by the crack significantly exceed the width of its opening *δ* »*r*, *L*» *r*; the air density is constant, *ρ* = *const*; the air flow in the air layer occurs at sufficiently low Reynolds numbers, so inertia terms in the basic equations of dynamics can be neglected.

When the properties of the body in the coordinate change insignificantly, it is permissible that the corresponding coefficients in the study of transport phenomena be taken to be constant or equal to their average effective values. However, in a number of cases the heterogeneity of the physical properties turns out to be so significant that it requires additional study.

For the convection-diffusion model equation through a crack, we use the Galerkin method [9]. The geometric dimensions of the investigated area and its sections (the linear dimensions of the surface formed by the crack considerably exceed the width of its opening *δ* »*r, L*» *r*), the pressure drop on the inner and outer sides of the building are necessary for calculation of the initial parameters. The motion of air for the scheme under consideration can be described by the Navier-Stokes equations. With respect to thin layers of the air medium, one can write down a system of equations that includes the equations of dynamics and the continuity equation:

$$\left.\begin{array}{l} \frac{\partial P}{\partial x}=\mu\cdot\frac{\partial^2 U}{\partial z^2}, \qquad \frac{\partial \mathrm{P}}{\partial \mathrm{y}}=\mu\cdot\frac{\partial^2 \mathrm{V}}{\partial \mathrm{z}^2}, \qquad \frac{\partial \mathrm{P}}{\partial \mathrm{z}}=0 \\ \frac{\partial \rho}{\partial \tau}+\frac{\partial(\rho\cdot U)}{\partial x}+\frac{\partial(\rho\cdot V)}{\partial y}+\frac{\partial(\rho\cdot W)}{\partial z}=M \end{array}\right\}, \tag{1}$$

where *P* - the excess pressure in the gap, Pa; *U, V, W* - velocity of the medium along the coordinate axes, *x, y, z,* m / s; *ρ* - density of air, kg / m^3; *τ*- time, s; *M* - the mass air flow per unit time per unit volume occupied by the crack, kg / m^{2}s; *μ* - the dynamic viscosity of air, N s/m^2.

Integrating twice the first and second equations of system (1) twice, given by boundary conditions, we represent it in integral form:

$$\int_0^r \frac{\partial(\rho\cdot U)}{\partial x}dz+\int_0^r \frac{\partial(\rho\cdot V)}{\partial y}dz+\int_0^r \frac{\partial(\rho\cdot W)}{\partial z}dz=\int_0^r M\cdot dz\,, \tag{2}$$

Equation (2), taking into account the assumptions and integration, can be transformed to the form:

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{12\cdot Q\cdot\mu}{r^3\cdot L^2\cdot A}=0\,, \tag{3}$$

where $M=\frac{Q\cdot\rho}{A\cdot L^2\cdot r}$, Q - volume flow of air entering the air layer, m^3 / s; *A* = *δ* / *L*, where *δ*, *L* are the characteristic dimensions of the crack, m.

Let us turn to the dimensionless form of the recording due to the proper choice of scale.

Let $\frac{r^3\cdot L^2\cdot A}{12\cdot Q\cdot\mu}=k$, *Pk* = *P* *, and for convenience of the solution we introduce the relative variables $\bar{x}=\frac{x}{L}$, $\bar{y}=\frac{y}{L}$, and we obtain the Poisson equation for P *:

$$\frac{\partial^2 P*}{\partial \bar{x}^2}+\frac{\partial^2 P*}{\partial \bar{y}^2}+1=0\,, \tag{4}$$

We write down the boundary conditions for equation (4):

$$P^*=0 \text{ for } \bar{x}=\pm 1 \text{ and } \bar{y}=\pm 1, \tag{5}$$

We choose a test function in the form of a trigonometric series:

$$P^*=\sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij}\cdot\cos\left(i\cdot\frac{\pi}{2}\cdot\bar{x}\right)\cdot\cos\left(j\cdot\frac{\pi}{2}\cdot\bar{y}\right), \tag{6}$$

where i = 1,3,5,…; j = 1,3,5,…; c_{ij} – are indeterminate coefficients.

Substituting expression (6) in (4) we obtain a nonzero residual *R*. The unknown coefficients can be determined from the system of equations composed of the inner products of the discrepancy *R* and the analytic functions φ_k of the trial solution, that is :

$$(R, \varphi_k)=\iint_D R\cdot\varphi_k\cdot d\bar{x}\cdot d\bar{y}=0, \tag{7}$$

where k = 1,2, ... N is the number of terms of the series in the trial solution; D - the solution region of the problem;

$$\varphi_k= \cos\left(i\cdot\frac{\pi}{2}\cdot\bar{x}\right)\cdot\cos\left(j\cdot\frac{\pi}{2}\cdot\bar{y}\right), \tag{8}$$

$$R=1-\sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij}\cdot\cos\left(i\cdot\frac{\pi}{2}\cdot\bar{x}\right)\cdot\cos\left(j\cdot\frac{\pi}{2}\cdot\bar{y}\right)\cdot\left[\left(i\cdot\frac{\pi}{2}\right)^2+\left(j\cdot\frac{\pi}{2}\right)^2\right], \tag{9}$$

The solution of the system of equations (7) makes it possible to obtain the value of the coefficient c_{ij} and the solution of the problem can be written in the following form:

$$P^*=\left(\frac{8}{\pi^2}\right)^2\cdot\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{(-1)^{\frac{(i+j)}{2}-1}}{i\cdot j\cdot(i^2+j^2)}\cdot\cos\left(i\cdot\frac{\pi}{2}\cdot\bar{x}\right)\cdot\cos\left(j\cdot\frac{\pi}{2}\cdot\bar{y}\right), \tag{10}$$

Performing the reverse substitutions and transforming equation (10), we obtain the dependence of the air flow through the crack on its dimensional characteristics and pressure:

$$Q=\frac{P\cdot r^3\cdot L^2\cdot A}{12\cdot\eta\cdot B}, \tag{11}$$

where

$$B=\left(\frac{8}{\pi^2}\right)^2\cdot\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{(-1)^{\frac{(i+j)}{2}-1}\cdot(-1)^{\frac{(i+1)}{2}-1}\cdot(-1)^{\frac{(i+1)}{2}-1}}{i\cdot j\cdot(i^2+j^2)} \tag{12}$$

Equation (11) allows you to determine the flow characteristics of outdoor air passing through a through crack in the enclosing structure, taking into account its linear dimensions and the magnitude of the excess pressure.

Equation (16) and the corresponding graph of the dependence on (Figure) make it possible to determine the flow characteristics of the external air passing through the through crack in the enclosing structure taking into account its linear dimensions and the magnitude of the overpressure.

The dependence of the air flow rate change (Figure) Is adopted for the following conditions: crack length $2\cdot L$ = 1 m, opening width r = 0.5 ... 6 mm, at which the laminar flow regime is observed, and the air pressure difference on the outer and inner sides Fencing structure P = 0 ... 100 Pa. Analysis of figure shows that with a crack opening width of up to 1 mm, the air flow through the slot is not significant; as well as through the pores of the fence. With a crack opening width of more than 2 mm, the airflow through the fence increases sharply.

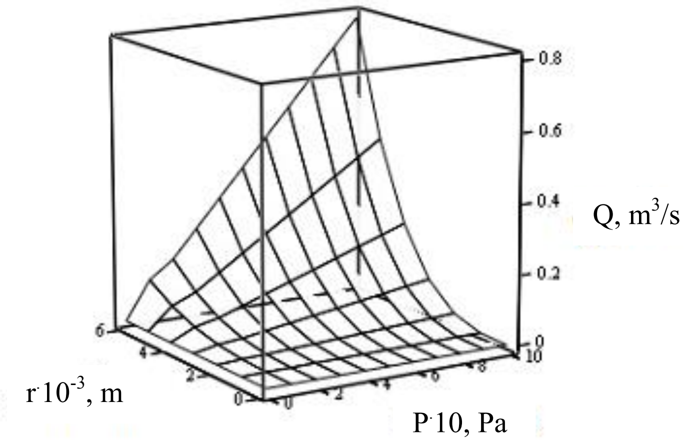

Figure. Dependence of air consumption on crack opening width and pressure drop inside and outside the building

With a crack opening width of 4 mm or more and a pressure drop on the inner and outer side of the enclosing structure of more than 20 Pa, increased air infiltration occurs.

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