Ventilated facade integrated with the HVAC system for cold climate

Вентилируемые фасады, интегрированные с инженерными системами здания для холодного климата

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Ключевые слова: термогравитационная конвекция; замкнутый термогравитационный контур; гидравлика воздушных потоков; энергоэффективность зданий и сооружений; тепломассоперенос; ресурсосбережение; конструктивное энергосбережение

Abstract. The application of convective heat transfer for air mass displacement in ventilation systems without the mechanical draft (integration of Double Skin Facade with HVAC Systems of the building) has a real practical perspective for Building energy performance. The purpose of this article is development of the theory of heat and mass transfer in capillary-porous media, air flows and building structures. The engineering purpose is a concept development of a closed ventilating circuit with convective heat flow to reduce the pressure on the environment, improve the comfort of the building and reduce operating costs. The subject of this research is a closed ventilating circuit with convective heat flow in constructive energy system (ventilated facade integrated with the HVAC system). It was the mathematical modeling of convective heat flow in ventilated facades. Based on the results obtained the concept of a closed ventilating circuit with convective heat flow is developed. The proposed system uses Convective heat transfer in a ventilated facade for the ejection and injection facilities, heat recovery in the buffer zone of the façade. It allows reducing ecological pressure on the environment and the application of energy resources.

Аннотация. Использование термогравитационной конвекции для перемещения воздушных масс в системах вентиляции без применения механического побуждения при условии интеграции вентиляционной системы с фасадными конструкциями здания имеет реальные практические перспективы. Целью данной статьи является развитие теории тепломассопереноса в гетерогенных средах, в том числе в капиллярно-пористых средах, воздушных потоках и строительных конструкциях. Технической целью статьи является создание концепции замкнутого вентиляционного контура (система вентиляции и кондиционирования, интегрированная с фасадными конструкциями) с термогравитационным течением, предназначенного для снижения экологического давления на окружающую среду, повышения комфортности здания и снижения эксплуатационных затрат. Объектом исследования является замкнутый термогравитационный контур в системе конструктивного энергосбережения (фасадные конструкции, интегрированные с системами вентиляции и кондиционирования). Разработана математическая модель замкнутого вентиляционного контура с термогравитационным течением, не требующая механического оборудования для организации движения воздуха. Предлагаемая система использует термогравитационную конвекцию в вентилируемом фасаде для эжекции и инжекции в

помещениях, рекуперацию теплоты в буферной зоне фасада, что позволяет снизить экологическое давление на окружающую среду, сократить использование невозобновляемых энергетических ресурсов.

1. Introduction

Control of indoor climate systems, ventilation, heating and air conditioning systems usually implies a high energy and economic costs. For heat exchange between the flows of supply and exhaust air are typically used air-to-air heat exchangers. Heat exchangers produce a transfer of tangible (visible) energy due to temperature difference on the surfaces. However, after a long period, the temperature difference between the air flows in the air intake is usually reduced and as a consequence some of the energy becomes insignificant. Another typical energy-saving solution is the introduction of ventilated facades using external or internal air, for reduction of thermal loads [1–5].

The design principles of envelope structures with the use of modern technology "active energy efficiency" and the recovery heat flow are investigated in the works [6–11]. The paper presents data on the transmission of heat recovery and special organization of the admission conditions of a flow of external air and its subsequent passage through the building envelope. The scientific groups provide theoretical and experimental data on the study of integration of ventilated facade systems with ventilation systems [12–14].

The combination of these technologies allows for the recovery of thermal energy and represents the implementation of the building envelope, mechanical ventilated exhaust the internal air outlet of the ventilated façade must have a temperature lower than the outdoor temperature in summer or in winter [15-16].

In the article [17-18] a numerical study of the efficiency of integrated energy-saving system consisting of a mechanically ventilated opaque façade and air-to-air heat exchanger. The transfer of energy from an external flow of air to the inside, leaving an air gap.

Exhaust air in the ventilated facade is subjected to a process of evaporative cooling at the beginning and throughout the height of the building.

In [19] numerical modeling for light frame building structures having different values of the resistance of heat transfer for different external conditions and for various internal heat loads. The energy efficiency of the proposed system is compared with efficiency of conventional systems: the traditional wall with an air gap and a recovery system of air, where the air is transferred from the supply system to exhaust the air and out of the building.

Currently, the typical functioning of the systems of ventilation and conditioning of modern buildings directly associated with high energy consumption for moving large volumes of air masses and maintain the required parameters of the microclimate (humidity, temperature, carbon dioxide concentration). They are designed, usually with the use of inefficient mechanical equipment and require additional allocation of usable space and volume to accommodate and service and the relevant regulatory measures for their maintenance. To operate such a relatively inefficient system consumes considerable additional non-renewables, accompanied by additional environmental pressure on the environment [20–24].

One of the promising directions in the construction is high-rise buildings. One of the many tasks due to the altitude is the specificity of the design and installation of ventilated façade system.

The metal thin-walled structure of the hinged facade works separately from the main wall. In this regard, with the incorrect method of calculating the facade structure, there is a risk of deformation of the structure and its further collapse [25–29].

The systems of ventilation and conditioning with rare exceptions do not provide for integration with façade and limited use of the capabilities of thermo-gravitational convection.

It is obvious that there is a real practical prospects for the use of thermo-gravitational convection for movement of air masses in ventilation systems without the use of mechanical impulses when integrated ventilation system with front designs of the building. Maintenance of such a system would not require energy resources, reducing ecological pressure on the environment, increases the comfort of the building and dramatically reduce maintenance costs.

The purpose of this article is development of the theory of heat and mass transfer in capillary-porous media, air flows and building structures. The engineering purpose is a concept development of a closed ventilating circuit with convective heat flow to reduce the pressure on the environment, improve the comfort of the building and reduce operating costs.

The subject of this research is a closed ventilating circuit with convective heat flow in constructive energy system (ventilated facade integrated with the HVAC system).

2. Methods

2.1. The development of hydraulic methods for solving problems of heat-gravitational convective flows

The main applied mathematical apparatus is numerical modeling of flows and fields of conservative impurity (temperature and moisture concentration) in licensed packages of programs using difference and variational-difference methods for solving parabolic and elliptic systems of equations (motion, momentum transfer, energy, impurity, heat propagation), allowing to obtain so-called "strong" solutions in the topology of uniform grid convergence. For validation of the numerical methods, it is planed to conduct full-scale physical experiments.

Processing and verification of experimental data is carried out using standard packages of mathematical statistics. Since technical solutions in the field of energy-efficient construction are mainly focused on normative materials produced empirically, the unity of the methods used to solve the problems of building Thermophysics can be seen in the theory of heat and mass transfer of solid and elastic capillary-porous bodies forming heterophase systems.

Currently, all known approaches to solving problems for such systems have insufficient connection with the basic provisions of the physics of surface phenomena. Therefore, it is planned to develop a physical model of non-stationary processes of interconnected heat and mass transfer taking into account the intensity of mass transfer between phases, thermocapillary flows, conditions of mechanical and dynamic equilibrium on curved surfaces of the phases. It is also assumed to propose and justify the rheological model of heterophase systems, characterized by the possibility of application in a wide range of unstable temperature and humidity conditions.

Next, we formulate the system of differential equations and boundary conditions for the nonstationary heat and mass transfer with account of capillary forces in the capillary-porous media taking into account the thermodynamics and physics of surface phenomena, with one voice describes the filtering process in case of incomplete saturation with the aim of optimizing the process of heat transfer and management.

The theory of heat-gravitational convective flows should not be considered by hydrodynamic theory of heat-gravitational convection with its set of methods and solutions including the theory of jet boundary layers [30–33].

Below the basic position of the hydraulic theory of heat-gravitational convective flows are listed in a dogmatic form. In part it demonstrates the possibilities of this theory and it is adapted for simple solutions of specific ventilation's problem.

The hydraulic calculation methods of heat-gravitational convective flows are based on the following assumptions:

1). The Boussinesq approximation: the pressure distribution in the heat-gravitational convective flows is hydrostatic:

$$\frac{dp}{\rho} + gdz = 0$$
,

where z – is a vertical coordinate [3]

The momentum equation at the vertical plane has the form:

$$u_z \frac{\partial u_z}{\partial z} + u_y \frac{\partial u_z}{\partial y} = g\theta + \frac{\partial \tau}{\partial y}$$
,

where τ – is the friction force, $u_{z,y}$ – components of the velocity vector u, y – is a coordinate directed across the flow, $\theta = \dfrac{T - T_c}{T_h - T_c} \in (0,1)$, T_c<T_h;

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2). It is considered that heat-gravitational convective flows – is a barotropic flow, p = p(ρ). More precisely the condition of barotropicity is replaced by the condition of polytropes: $p = p_0 \left(\dfrac{\rho}{\rho_0} \right)^n$, with the polytropic exponent n. In the case of thermal equilibrium (stationary gas), n=k, k – for a perfect diatomic gas (air) k=7/5. In the case of barotropic motion with the supply of heat from the hot wall: n<k. Then if 1<n<k, it is the cooling air in the flow's direction. If n<1, the air is continuously heated in the direction of heat-gravitational convective flows.

3). The polytropic exponent n is uniquely determined by the intensity of heat exchange between the air and the hot wall. If $S_t=0 \rightarrow n=k$; $S_t=\infty$, n=1. Then, for example, when 1<n<k at a convenient approximation $n = k - (k-1)\text{th}St, St = arth\dfrac{k-n}{k-1} = \ln\sqrt{\dfrac{2k-n-1}{n-1}}$, 1<n<2k-1, where $St := \dfrac{\alpha}{\rho C_p v}$ - the Stanton's number, α - the coefficient of heat transfer from hot wall to the stream, v – the average velocity in heat-gravitational convective flows;

4). The momentum equation contains 3 density distribution sought for (pressure and 2 components of velocity). A system of equations is compiled: the momentum equation is contained by the energy equation and the displacement continuity equation. The density associated with the barotropic pressure connection (barotropicity condition). In the hydraulic version of heat-gravitational convective flows the density distribution are replaced by the distributions: velocity by average velocity, temperature by average flow temperature.

5). The corresponding equality are formulated for the integral distribution:

$$v = \varphi\sqrt{2gL\left(1 - T_c / T_h\right)},$$

$$\frac{dT}{d\overline{x}} + StT = StT_h,$$

$$\dot{m} := \rho v h = const,$$

where h – channel width, L – its length, φ – velocity coefficient, $\varphi = \dfrac{1}{\sqrt{1+\zeta}}$, ζ – pressure loss factor [3].

The first relation is a consequence of energy integral (Bernoulli) for the heat-gravitational convective flows, and the second relation is a consequence of the first start to flow in a heated channel (the condition of entropy balance) and finally, the third relation is the displacement continuity condition.

The dependence is fair for average velocity [4]:

$$v = \varphi\frac{gL}{\sqrt{RT_c}}\sqrt{\frac{1}{n} - \frac{1}{k}},$$

R – the individual gas constant. For air, approximately, R=287 $m^2/(s^2 K)$.

Then: $v = \varphi\dfrac{gL}{\sqrt{RT_c}}\sqrt{\dfrac{k-1}{k}} \approx \dfrac{\varphi}{2}\dfrac{gL}{\sqrt{RT_c}}.$

The last expression in dimensionless form is possible to write in "similarity criterion":

$v/\sqrt{gL} = \dfrac{\varphi}{2}\sqrt{\dfrac{gL}{RT_c}}$. Indeed, $v/\sqrt{gL} := Fr$ – the Froude number for heat-gravitational convective flows, $\sqrt{gL/RT_c} = Ba$ - number Barstow, measuring the ratio of the Lagrangian velocity $\sqrt{gL}$ to the velocity of sound in cold air, $\sqrt{RT_c}$. Then:

$$Fr/Ba = \varphi\sqrt{\frac{k-1}{k}} = \varphi/2 \quad,$$

$$\text{or} \quad Fr = \varphi\sqrt{2(1-T_c/T_h)}.$$

The use of variables similarity is convenient for simulations of real building structures in laboratory settings (Fig.1)

Figure 1. Physical model

6). For a real air flow in heat-gravitational convective flows the assessment is evaluated $\frac{v^2}{2} << \frac{p}{\rho}$.

Therefore the integral of the kinetic energy can be neglected velocity head [3];

7). For example, if the vertical ventilation manifold with constant cross section A is equal to the releases section A_e and coefficient loss factor ζ. Let, further, an icon 1 shows the flow parameters in the reservoir before release, icon 2 – after the release and the icon e in the news. Given: velocity v_1, pressure p_1, square section of the vent of the collector editions, A, A_e. Find the velocity and velocity distribution along the length of the manifold [5]. The equation of balance of kinetic energy with the use limitations of paragraph 6 is:

$$p_1 A v_1 = p_2 A v_2 + p_e A_e v_e + \zeta A_e \rho \frac{v_e^2}{2},$$

$$p_2 = p_1 - \frac{\rho}{2}\left(v_1^2 - v_2^2\right) = p_1 - \frac{\rho}{2}\left(v_1^2 - (v_1 - nv_e)^2\right) n := A_e/A < 1.$$

We assume p_e=0. Then the sequence of velocities in the sections between the editions forms a geometric progression:

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- after the first issue: $v_2 = v_1 \dfrac{\zeta - n}{\zeta + n}$;

- after any k-1 issue: $v_k = v_1 \left(\dfrac{\zeta - n}{\zeta + n} \right)^k$;

- velocity in k issue:

$$v_{e,k} = n^{-1}(v_{k-1} - v_k) = n^{-1} v_1 z^{k-1}(1-z), k = 2(1)\omega, z := \frac{\zeta - n}{\zeta + n} < 1,$$

ω – the number of issues:

- pressure on any part of the header $p_k = p_{k-1} - \rho/2\left(v_{k-1}^2 - v_k^2\right)$.

Then it turns out that to align the costs of air releases and average velocity along the length of the collector it is necessary to design issues so that the least z different from 1, i.e. to either $\zeta \gg 1$, or $n \ll 1$, either simultaneously fulfill both inequalities. Real air editions of the condition n<0,1 guarantees the homogeneity of the flow releases;

8). Dissipation power flow in the collector of the ventilation shaft is determined by the standard according to the formula:

$$P_w := \frac{1}{2} \rho A \sum_{k=2}^{\omega} v_{k-1}\left(v_{k-1}^2 - v_k^2\right) = \frac{1}{2} \rho A v_1^3 \sum_{k=2}^{\omega} z^{2(k-1)}(1-z) = \frac{1}{2} \rho A v_1^3 \left(1 - z^{2\omega}\right).$$

If the number of issues $\omega \gg 1$, then $P_w \leq 1/2 \rho A v_1^3$. Power dissipation by releases is

$$P_w^{(e)} = \frac{1}{2n} \rho A_e v_1^3 \zeta\left(1 - z^\omega\right) \leq \frac{1}{2n} \rho A_e v_1^3.$$

For example, if A=1 m², v=20 m/s, air density is standard, ρ = 1.19 kg/m³, the dissipation heat in the collector capacity will be the quantity of the order 4 kW. The same power dissaperaed on releases. The total value of dissipation heat power is about 8kW. Taking into account the efficiency of the ventilation installation, the electric power consumption will be approximately 10 kW. Supplied with a ventilation manifold in space consumption will be about 70000 m³/h. It is easy to recalculate the vent manifold to any other air flow;

9). Hydraulic theory of heat-gravitational convective flows intersects with accurate hydro-mechanical theory in the model boundary layer. The fact is that, in vertical channels when the Rayleigh numbers

$$Ra := \sigma \frac{gL^3}{v^2} \frac{T_h - T_c}{T_h} \leq 10^9,$$ heat-gravitational convective flows are laminar. The near-wall

boundary layer lift force has a thickness $\delta = \sqrt[4]{\dfrac{v^2 x}{g}}$, σ – Prandtl number, a maximum of a few millimeters

and never fills the entire vertical width of the ventilated channel, contrary to the assertions of some authors [7].

In these circumstances the description of the flow is reduced to limit the problem of Case [6] for the dimensionless stream function $f := \psi / \sqrt{vdz}, f \in (0, a)$ and the dimensionless temperature difference

$\theta := \dfrac{T - Tc}{T_h - T_c} \in (0.1)$. It is considered that f=f(ζ), θ=θ(ζ), ζ:=y/δ, 0<ζ<∞. We denote the derivative touches

the requed distributions f and θ variable ζ. Then f'=df/dζ proportional to the local longitudinal velocity in the boundary layer, f''=d²f/dζ² proportional to the friction, θ'=dθ/dζ proportional to the heat flow across the heat-gravitational flow from the hot wall. The ultimate objective of Case can be formulated as follows:

$$f^{'''} + 3ff^{''} - 2f^{'2} + \theta = 0,$$

$$\theta^{''} + 3\sigma f \theta^{'} = 0,$$

$$f(0) = f'(0) = \theta(0) - 1 = \theta(\infty) = f^{'}(\infty) = 0.$$

Main results:

- velocity distribution $f^{'}(\zeta) = \zeta \exp(-3\sigma a\zeta)$ and the maximum velocity are near the hot wall. The velocity profile is the same as in grazing torch (wall jet);

- temperature distribution $\theta = \exp(-3a\sigma\zeta)$;

- the distribution of friction decreases in ζ from a maximum value at the hot wall, $\zeta=0$, to zero outside the boundary layer, $\zeta=\infty$: $f^{''}(\zeta) = \exp(-3a\sigma\zeta) - 3a\sigma\zeta \exp(-3a\sigma\zeta)$;

- the heat flux distribution is monotone-decreasing quantity of ζ: $\theta^{'}(\zeta) = 3a\sigma \exp(-3a\sigma\zeta)$.

Having a local velocity profiles and temperature difference, it is easy to spend an averaging across the width of the channel and the flow rate and find the hydraulic distribution (average velocity and average flow temperature).

2.2. Optimization of the heat and mass transfer in systems of constructive energy saving

To minimize heat losses through the external envelope the research of flow and heat transfer in capillary-porous medium in building structures.
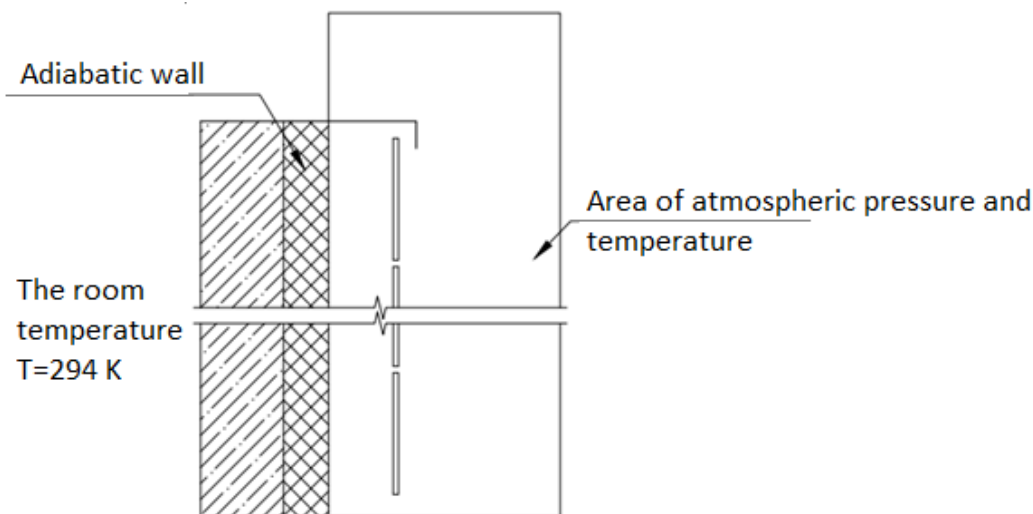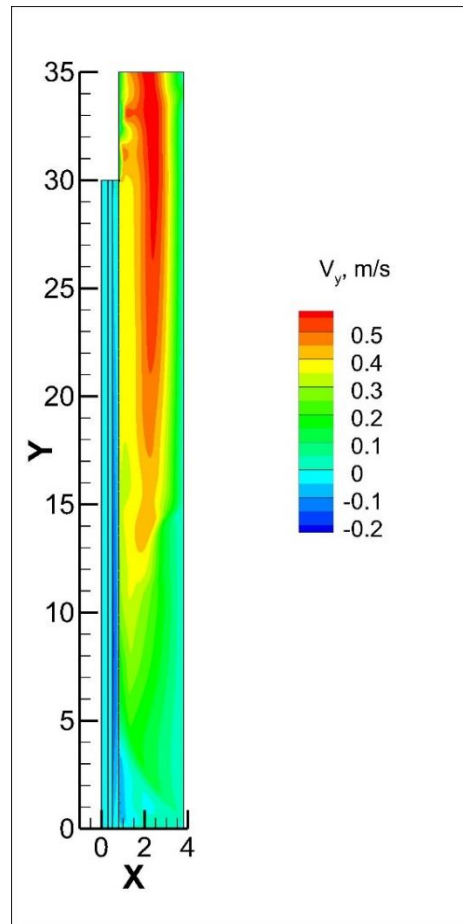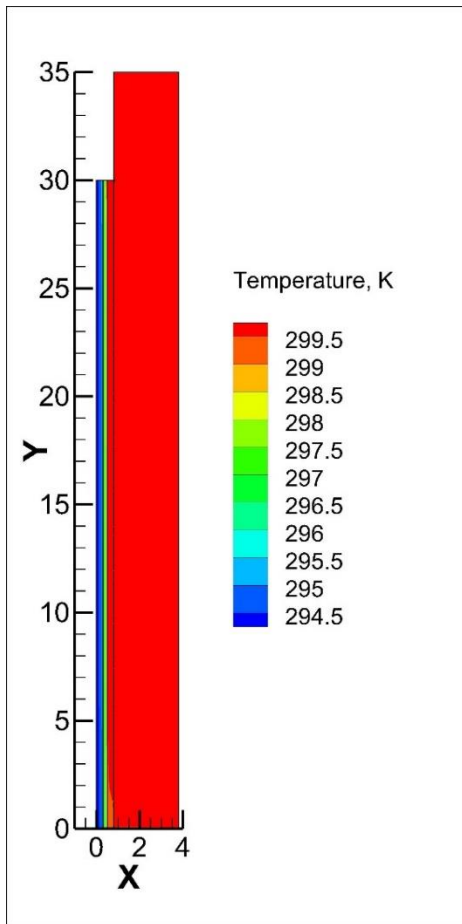

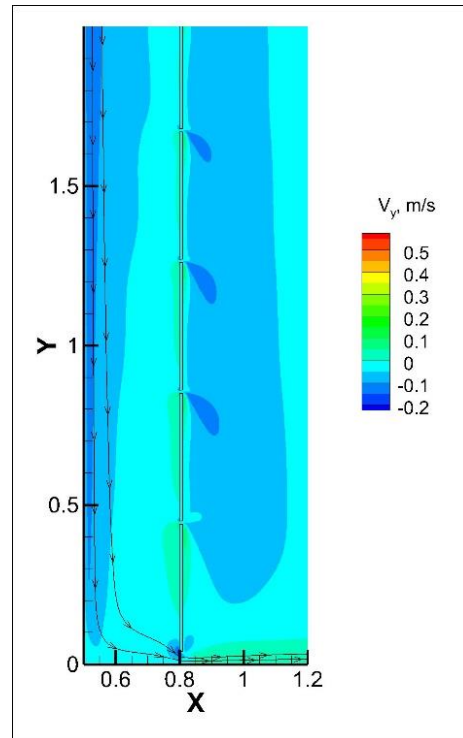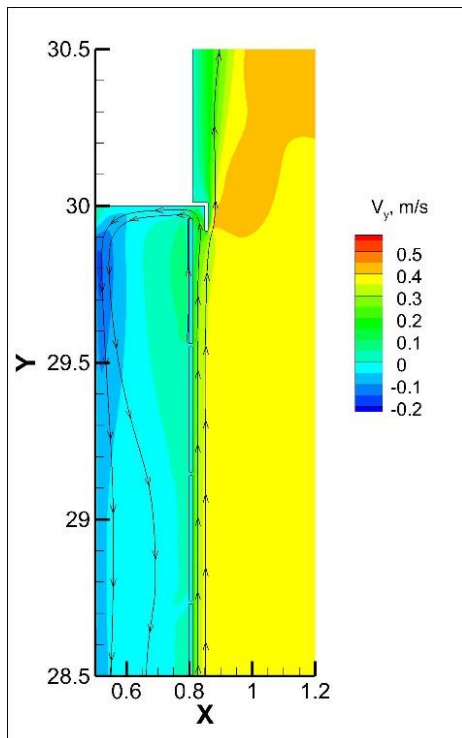**Figure 2 The estimated model of the external envelope**

To calculate the following temperatures is used:

• 235.4 K the regions with large difference in temperature throughout the year;

• 289.8 K – the temperature outside equals the temperature of the outer surface of the insulation;

• 300 K – high ambient temperature.

Below there are results of calculations for different climatic zones for buildings with a height 30m

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Figures 3–4. Isotherms, isolines of velocity (d=300mm L=30m.T=300K)

Figures 5–6. Velocity vectors (d=300mm L=30m.T=300K) in the upper and lower parts.

3. Results and Discussion

In recent years the systems of ventilated facades are widely spread in different regions with different climatic conditions. This is due to the fact that modern ventilated facades possess such qualities as energy efficiency, reducing the influence of solar insolation on the microclimate inside the building, protection from noise impacts and a wide range of design solutions. Considering all these qualities of ventilated facades, the solution of the organization of heating and ventilation to the building to increase its efficiency is proposed.

Principles of design of envelope structures with the use of modern technology of "active energy efficiency" and the recovery heat flux are investigated [6–11]. The paper presents data on the transmission of heat recovery and special organization of the conditions of admission of a flow of external air and its subsequent passage through the building envelope. The scientific groups provide theoretical and experimental data on the study of integration of ventilated facade systems with ventilation systems [12–14]. In this paper the minor energy consumptions with respect to a basic configuration consisting of a traditional closed cavity wall and recovery equipment wherein energy is transferred from the outdoor air to the exhaust air extracted from within the building, are also calculated by introducing a cooling performance index and discussed in full details. A dimensional empirical correlation that expresses such cooling performance index as a function of the several independent variables considered is also proposed [15].

The thermo-circuit is shown at figure 7. In basis of thermo-circuit is the natural convection and the recovery of the energy expended for air heating in the facade. The principle of operation of the circuit as follows: air enters from the atmosphere through the rusty to the channel between the facade and insulation. Due to the temperatures difference on the thermal insulation and facade air is heated in the channel and begins naturally rising to the top. Next the heated air is collected around the perimeter of the roof and is supplied to filtration-pumping station. But before it get into it, the oxygen level of taking air mass are monitored (if the oxygen level is low, the filtration-pump system is able to collect air from the environment). Filtration-pumping system consists of three main elements: the numeral 1 is a high performance air pump high pressure; 2 – filter system (cyclone separator); 3 – heating device. After filtration and pumping the air gets into the ventilation shaft to the rooms to provide the necessary climate conditions. It is possible to adjust the resistance at the outlet of the ventilation ducts leading from the mine to the premises. To adjust the operation of the filtration and pumping system the sensors pressure is installed in the ventilation shaft, which you can adjust the mass flow in the circuit. Supply air to the rooms is carried out through the ducts in the floor. Due to the natural convection the heated air rises to the ceiling, then it gets into the output part of the ventilation system which leads the air back to the ventilated façade.
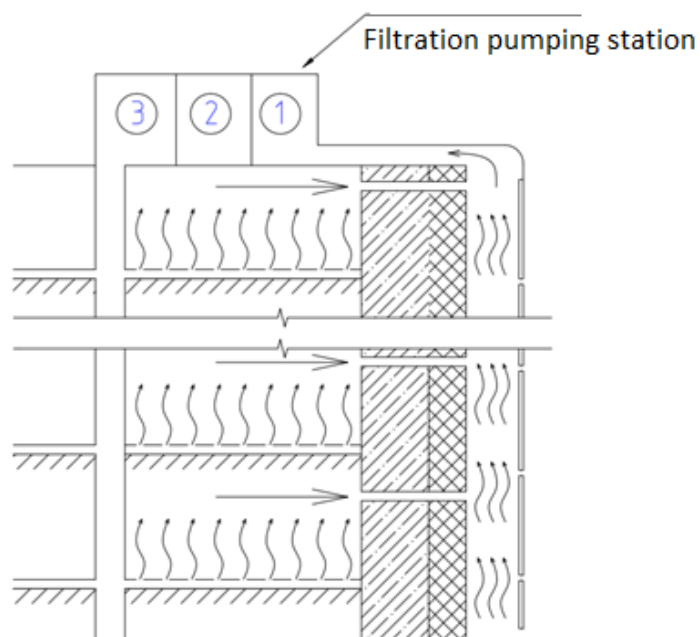

Figure 7. The closed ventilating circuit with convective heat flow

4. Conclusions

It is developed hydraulic methods of calculation of heat-gravitational flows, complicated heat and mass transfer, allowing proposing specific design solutions and reasonable methods of determining parameters and dimensions of the elements of the circuit. It is established that paving a local velocity profiles and temperature difference, it is easy to spend an averaging across the width of the channel and the flow rate and find the hydraulic distribution (average velocity and average flow temperature).

The concept of closed ventilating circuit with convective heat flow is developed (HVAC integrated with ventilated system facade) based on heat-gravitational convection, does not require mechanical equipment to air displacement. The proposed system uses thermo-gravitational convection in a ventilated facade for the ejection and injection facilities, recovery of heat in the buffer zone of the facade. The air flows in the facade through the holes on the outer face of the facade and perceive the warmth of the inner face of the facades and air flow induced from the premises. The buffer zone acts as a heat exchanger and is used as a heat-shielding layer of the building. In this system the air as incompressible fluid, the fluid obeying the laws of hydraulics. The velocity distribution $f'(\zeta) = \zeta \exp(-3\sigma a\zeta)$ and the maximum velocity are near the hot wall. The velocity profile is the same as in grazing torch (wall jet); the distribution of friction decreases in ζ from a maximum value at the hot wall, $\zeta=0$, to zero outside the boundary layer, the heat flux distribution is monotone-decreasing quantity by ζ.

It is offered the optimization of flows and heat transfer in systems of constructive energy saving: vertical constructions and ventilation systems to minimize the cost of power to move the coolant (air). (analytical calculations, the numerical experiments in specialized software systems, preparing a physical model).

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