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Numerical simulation of ventilated facades under extreme climate conditions

Численное моделирование вентилируемых фасадов в экстремальных климатических условиях

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Ключевые слова: вентилируемый фасад; численное моделирование; ограждающие конструкции; термогравитационное движение воздуха; средняя скорость; воздушный зазор; энергоэффективность

Abstract. To reduce the costs of building operation, it is necessary to provide for the use of energy-saving technologies at the stage of building design. This allows efficient use of material and energy resources, minimize costs during the design and construction of buildings and structures. One of the energy-saving technologies widely used in construction is the use of ventilated facade systems. Its application in difficult climatic conditions of many regions of Russia requires improvement and refinement of the existing methods of calculation of influence of temperature stresses in elements on strength characteristics of system, ways of the account of influence of air exchange in a backlash. The aim of the work is to determine the velocity of air flow in the gap of a ventilated facade with different width of the gap, the height of the building and climatic conditions by the method CFD (Computational Fluid Dynamics) - simulation of convective heat flux.

Аннотация. Для снижения расходов на эксплуатацию зданий необходимо предусматривать применение энергосберегающих технологий еще на стадии проектирования здания. Это позволяет рационально использовать материальные и энергетические ресурсы, минимизировать затраты на этапах проектирования и строительства зданий и сооружений. Одной из энергосберегающих технологий, широко применяемой в строительстве, является использование навесных вентилируемых фасадных систем. Её применение в сложных климатических условиях многих регионов России требует совершенствования и доработки действующих методик расчета влияния температурных напряжений в элементах на прочностные характеристики системы, способов учета влияния воздухообмена в зазоре. Целью работы является определение скорости воздушного потока в зазоре вентилируемого фасада при различной ширине зазора, высоты здания и климатических условий методом CFD (Computational Fluid Dynamics) - моделирования конвективного теплового потока.

1. Introduction

The object of study in the work are ventilated hinged system (Fig. 1), widely used to reduce heat loss and protect the walls from the adverse effects of the environment [1–5]. There are many approaches

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to the study of flow in such systems [6–10]. However, studies of convective flow in ventilated facades under critical climatic conditions have not been conducted yet [11–16].

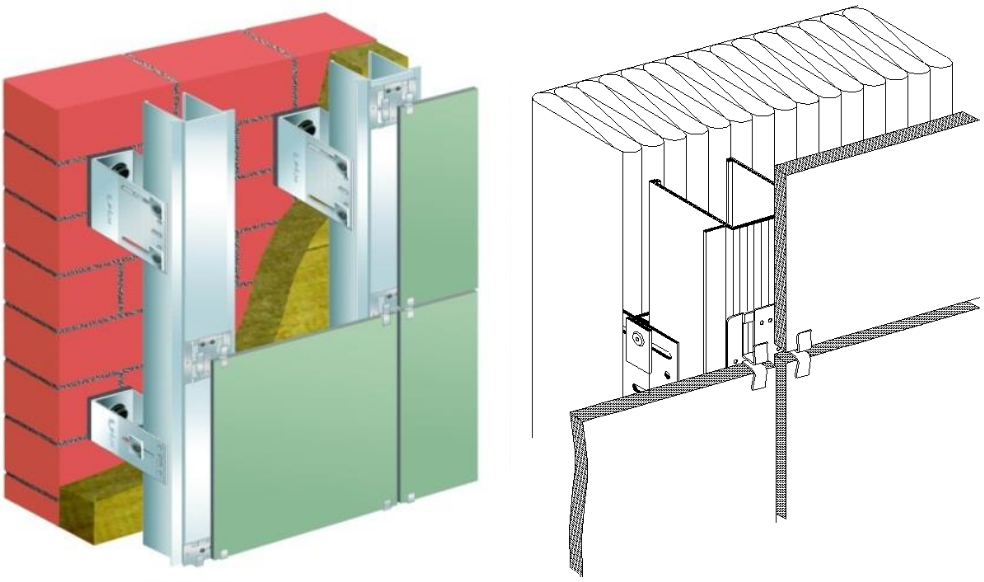

Figure 1. The design of hinged ventilated facades (axonometric perspective)

This construction technology was developed in Germany in the 1950s and has become widespread in various countries of the world, including our country, which led to the development of an international organization standardization of a number of international standards governing the methods of calculation and design of hinged facade systems.

These documents are constantly being improved, taking into account the physical properties of modern thermal insulation, building materials, especially the new construction of high-rise buildings, the reconstruction of existing buildings, the complexity of climatic conditions [17, 18].

In particular, the ISO/TC 163/SC 2 technical Committee has developed calculation methods covering the operational and thermal, hydrothermal, solar and optical characteristics of specific parts of a building, building components and components such as light-tight enclosures, Windows and facades. To a large extent, they summarize the results of studies conducted by various researchers [19].

Many of the works are related to the determination of the thickness of thermal insulation when taking into account the air exchange in the gap of the ventilated facade, the influence of metal thermal conductive inclusions by calculating the temperature fields and aimed at improving the individual bearing elements of the facade design. Thus, in [20] the program of transition systems modeling (TRNSYS) and its modification for modeling and control of air flow in buildings is used. Haase et al. [21] used TRNSYS to optimize glass facades in Hong Kong's hot and humid climate, López et al. [22] used this software to simulate the experimental module of an opaque ventilated façade. Many researchers use CFD modeling to solve similar problems [23, 24], which is an effective tool in the study and design of ventilated facades.

Thus influence of extreme climatic conditions in the operating standards and researches (sharp change of temperature of outside air from positive temperatures to negative and Vice versa at change of humidity, force of wind, falling of atmospheric pressure) on air movement in an air gap is affected poorly that significantly complicates justification of application of hinged front systems in many regions of Russia.

The aim of the work is to determine the speed of air flow in the gap of the ventilated facade with different width of the gap, the height of the building and climatic conditions. For its achievement the following tasks are solved:

- developed a CFD model of the ventilated system using the commercial package ANSYS Fluent;
- built grid;
- validation model was developed;
- comparison of simulation results with experimental data is performed.

The choice of research tool - CFD-modeling, due to the fact that it allows to provide an error of calculations within 3–5 %, comparable to the reliability of the full-scale experiment and significantly saves money and time on justification and confirmation of technical solutions.

2. Methods

Since the traditional experimental approach is expensive and does not provide complete information about the flow, it is reasonable to use the CFD approach. Computational Fluid Dynamics (CFD) is uses numerical analysis and data structures to solve and analyze problems that involve fluid flows and heat fluxes. With supercomputers, better solutions can be achieved.

The calculations were carried out on a finite volume mesh, that accurately reproduces the façade geometry with variable cell size and boundary layer refinement by solving the Reynolds-Averaged formulation of the Navier-Stokes equations (RANS). A common k-epsilon turbulence closure and blended wall functions for precise boundary layer flow computations are employed, yielding the convective heat transfer at the surface boundaries.

2.1. The development of numerical methods for solving problems of heat and mass transfer

The conjugate heat transfer is considered. A model was built for different heights of the building, in which the gap between the insulation and ceramics varies from 40mm to 300mm.

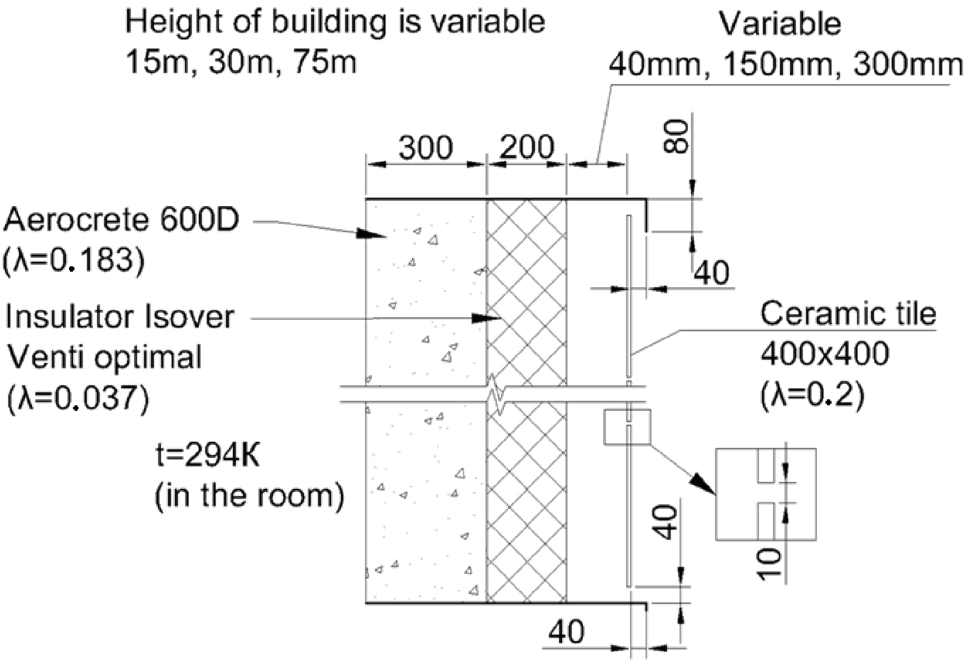

Figure 2. Design of the calculated wall

Convection and heat transfer in the presented calculation is described by the system of Navier-Stokes equations in their non-stationary formulation [25–28], taking into account the Boussinesq approximation. Decomposing the Navier-Stokes equations into the RANS equations makes it possible to simulate practical engineering flows, such as the airflow over an airplane. The assumption (known as the Reynolds decomposition) behind the RANS equations is that the time-dependent turbulent (chaotic) velocity fluctuations can be separated from the mean flow velocity. This reduces the problem to the calculation of the flow of an incompressible fluid and gas in the presence of a mass force proportional to the local temperature drop. This system of equations is as follows:

$$\nabla \cdot \boldsymbol{V} = 0$$

$$\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V}\nabla)\boldsymbol{V} = -\frac{1}{\rho}\nabla p + \nu\Delta\boldsymbol{V} + \boldsymbol{g}\beta T\boldsymbol{\gamma}$$

$$\frac{\partial T}{\partial t} + v\nabla T = a\,\Delta T$$

where $\boldsymbol{V}$ – fluid velocity; T – temperature; p – modified pressure; ρ – the average density; $\boldsymbol{g}$ – the acceleration due to gravity; ν – the kinematic viscosity coefficient, a – the thermal diffusivity coefficient; β – the coefficient of volumetric expansion; $\boldsymbol{\gamma}$ – the unit vector directed vertically upwards.

Entering the dimensionless variables: distance – h, time – h^2/ν, speed – $g\beta\Delta T\, h^2/\nu$, temperature – ΔT (temperature difference), pressure – $\rho g\beta\Delta T\, h$, we get the system:

$$\nabla \cdot \boldsymbol{V} = 0$$

$$\frac{\partial \boldsymbol{V}}{\partial t} + Gr\,[(\boldsymbol{V}\nabla)\boldsymbol{V_0} + (\boldsymbol{V_0}\nabla)\boldsymbol{V}\,] = -\nabla p + \Delta \boldsymbol{V} + T\boldsymbol{\gamma}$$

$$\frac{\partial T}{\partial t} + Gr\,[\boldsymbol{V}\nabla T_0 + \boldsymbol{V_0}\,\nabla T] = \frac{1}{Pr}\Delta T$$

The profiles of the velocity and temperature of the main flow are in the dimensionless variables V_0 and T_0 have the form:

$$V_0 = \frac{1}{6}(x^3 - x),\ T_0 = -x$$

The problem contains two dimensionless parameters that determine the similarity of convective flows – the Grashof and Prandtl number:

$$\mathrm{Pr} = \frac{\nu}{a},\ \mathrm{Gr} = \frac{g\beta\Delta T L^3}{\nu^2}$$

In most of the literature, when examining a freely convective flow, one more criterion is used, which determines our task – the Rayleigh number, which is constructed through two other dimensionless numbers:

$$\mathrm{Ra} = \mathrm{Gr}\cdot\mathrm{Pr}.$$

To solve the problem, the heat equation and the Reynolds-averaged Navier-Stokes equations (RANS), closed with the help of the k- epsilon model of turbulence, were solved. The k-epsilon model is one of the most common turbulence models, although it just doesn't perform well in cases of large adverse pressure gradients. It is a two equation model, that means, it includes two extra transport equations to represent the turbulent properties of the flow. This allows a two equation model to account for history effects like convection and diffusion of turbulent energy. The first transported variable is turbulent kinetic energy, k. The second transported variable in this case is the turbulent dissipation, epsilon. It is the variable that determines the scale of the turbulence, whereas the first variable, k, determines the energy in the turbulence.

On the boundary between two bodies, the condition of equality temperatures and flow was given.

Enhanced Wall Treatment was used to model the flow in the near-wall area. Enhanced wall treatment is a near-wall modeling method that combines a two-layer model with enhanced wall functions. If the near-wall mesh is fine enough to be able to resolve the laminar sublayer (typically $y^+=1$), then the enhanced wall treatment will be identical to the traditional two-layer zonal model (see below for details). However, the restriction that the near-wall mesh must be sufficiently fine everywhere might impose too large a computational requirement. Ideally, then, one would like to have a near-wall formulation that can be used with coarse meshes (usually referred to as wall-function meshes) as well as fine meshes (low-Reynolds-number meshes). In addition, excessive error should not be incurred for intermediate meshes that are too fine for the near-wall cell centroid to lie in the fully turbulent region, but also too coarse to properly resolve the sublayer.

The Boussinesq hypothesis was used to simulate the convection flow. The Boussinesq approximation is a way to solve nonisothermal flow, such as natural convection problems, without having to solve for the full compressible formulation of the Navier-Stokes equations.

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2.2. Boundary conditions

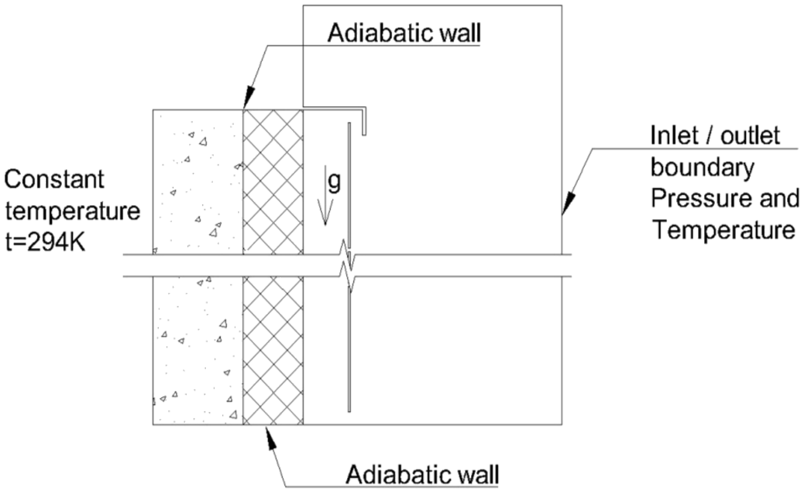

Figure 3. Research objective

The results presented below were obtained on meshes providing a mesh-independent solution.

Three temperatures were taken to calculate:

235.4 K (regions with a large temperature drop throughout the year);

289.8 K (the temperature outside the building is equal to the temperature of the external surface of the insulation);

300 K (the highest ambient temperature)

3. Results and Discussion

The highest speed of natural convection is observed in the largest gap. However, according to the norms, the speed of natural convection should not exceed 1 m/s. Therefore, it is not possible to install facades with a large gap in regions with a large average annual temperature difference.

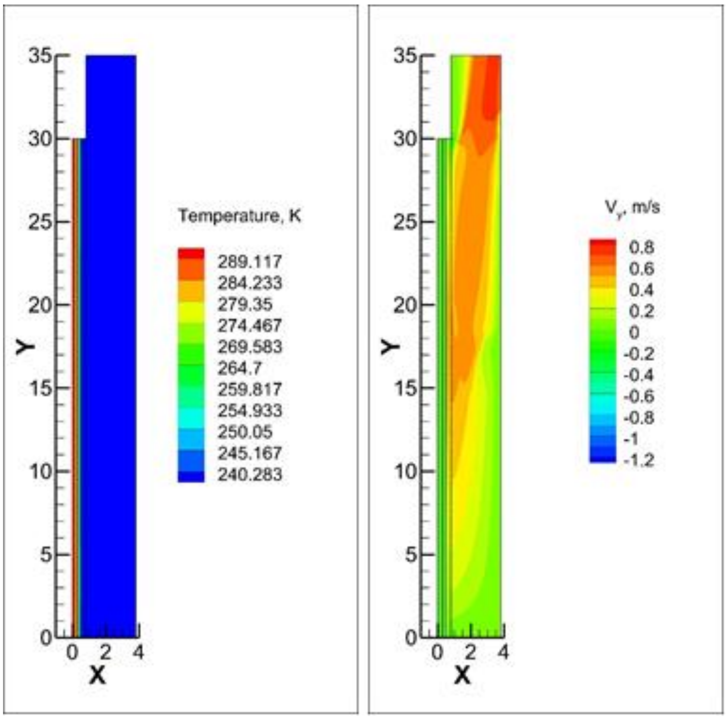

Figure 4. Isotherms, contours of velocity (d = 300 mm, L = 30 m, T = 235.4 K)

The diagrams show dimensionless velocity shape, temperatures and coordinates for comparing different gap values (40mm, 150mm, 300mm). The velocity is translated into a dimensionless quantity using the buoyancy velocity:

$$V_b = (g\beta\Delta TL)^{1/2}$$

Below the diagrams are just for the height that equal to 30 m. The velocity and temperature profiles are shown just in the middle of height (15 m).

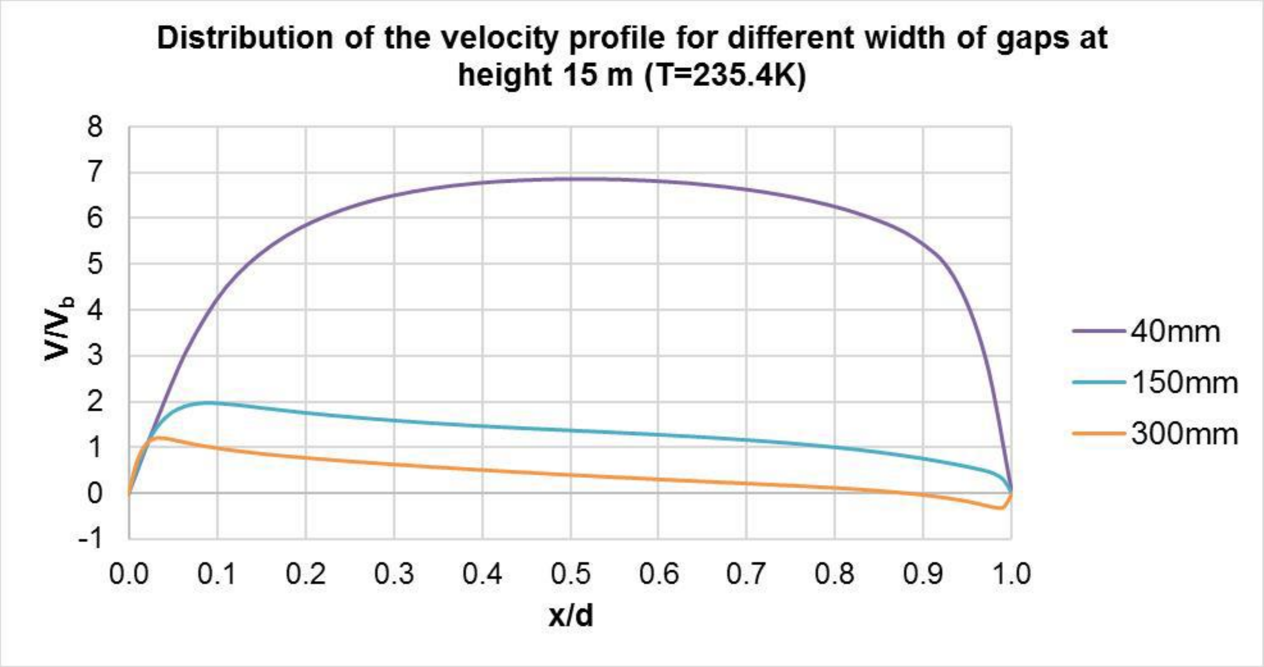

Figure 5. Distribution of the velocity profile for different width of gaps at height 15 m (T = 235.4 K)

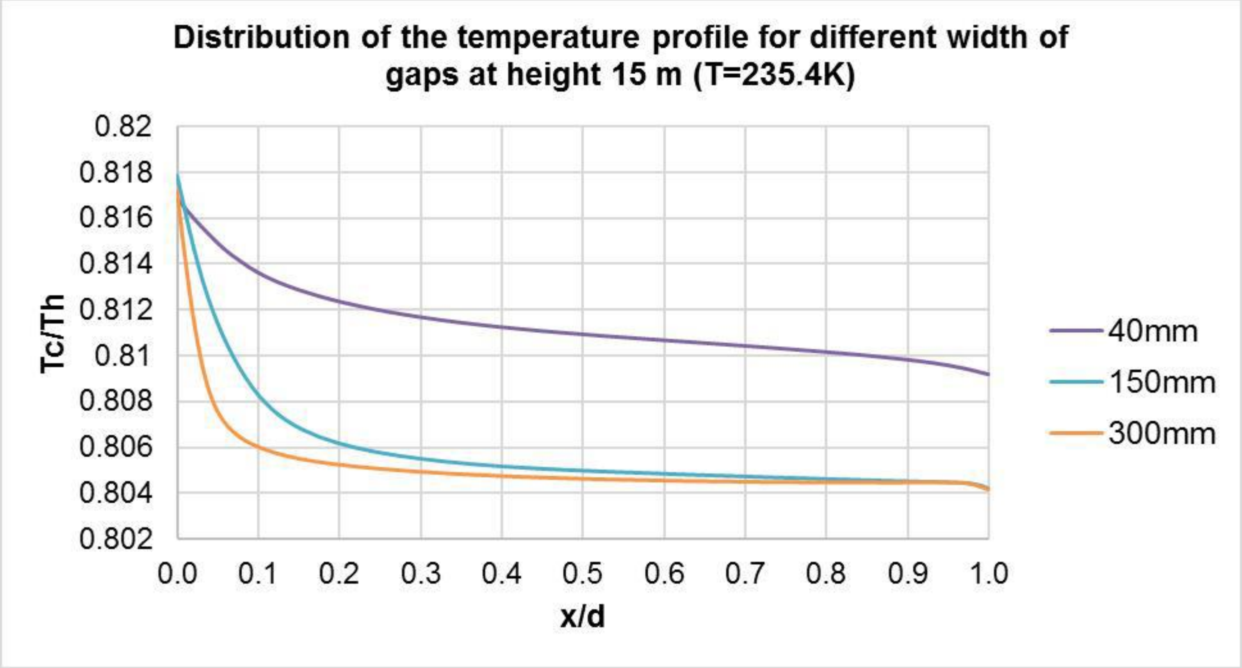

Figure 6. Distribution of the temperature profile for different width of gaps at height 15 m (T = 235.4 K)

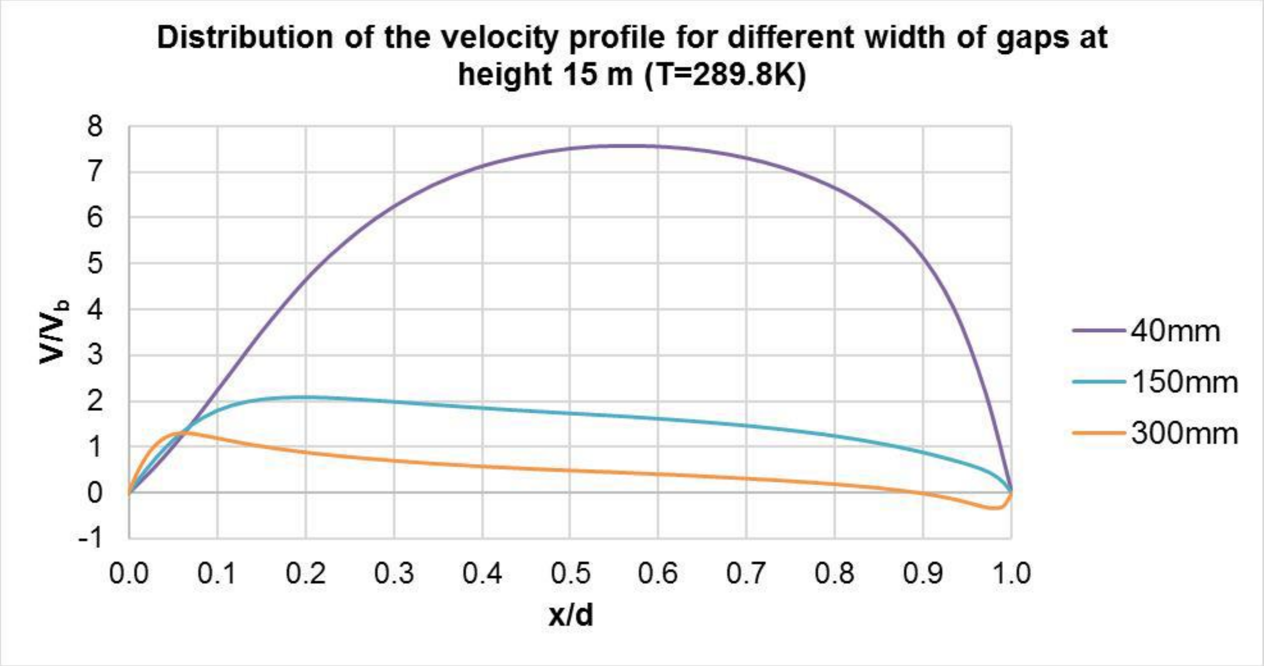

Figure 7. Distribution of the velocity profile for different width of gaps at height 15 m (T = 289.8K)

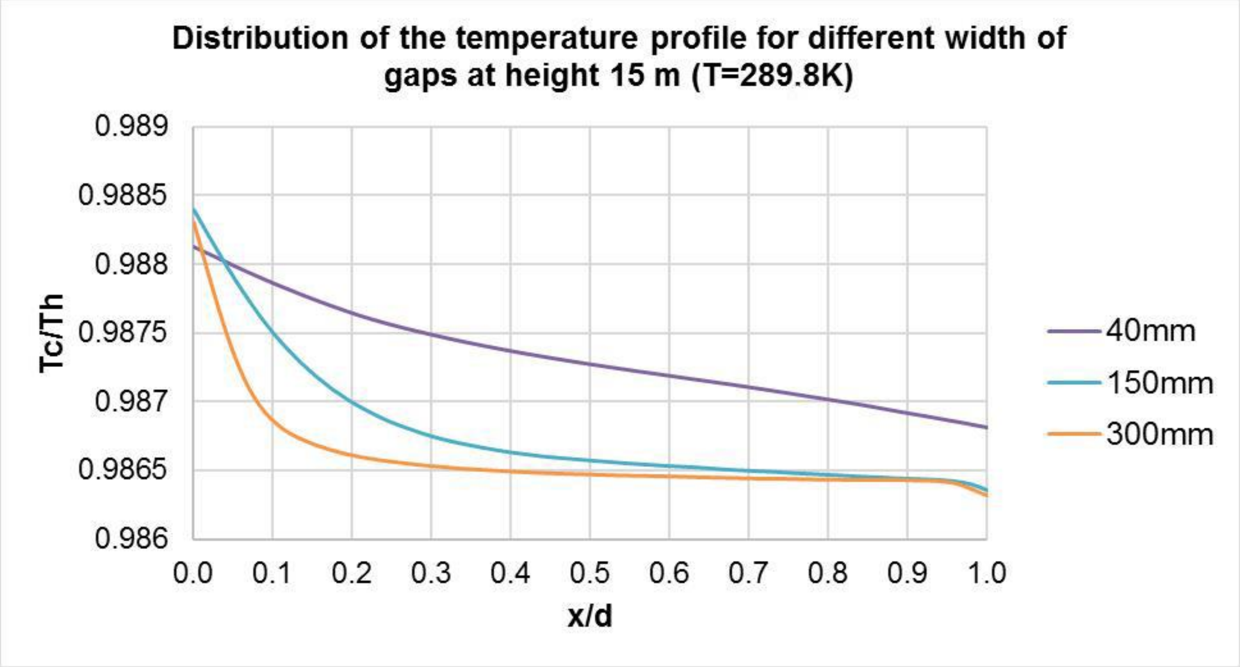

Figure 8. Distribution of the temperature profile for different width of gaps at height 15 m (T = 289.8K)

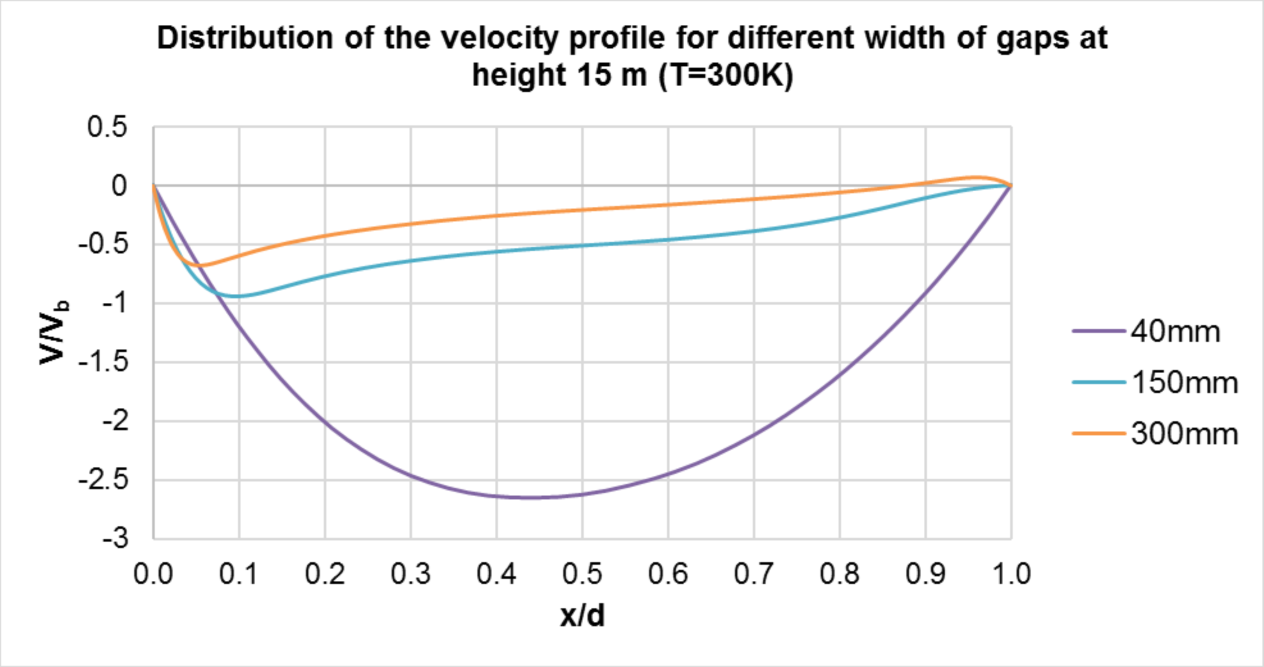

Figure 9. Distribution of the velocity profile for different width of gaps at height 15 m (T = 300 K)

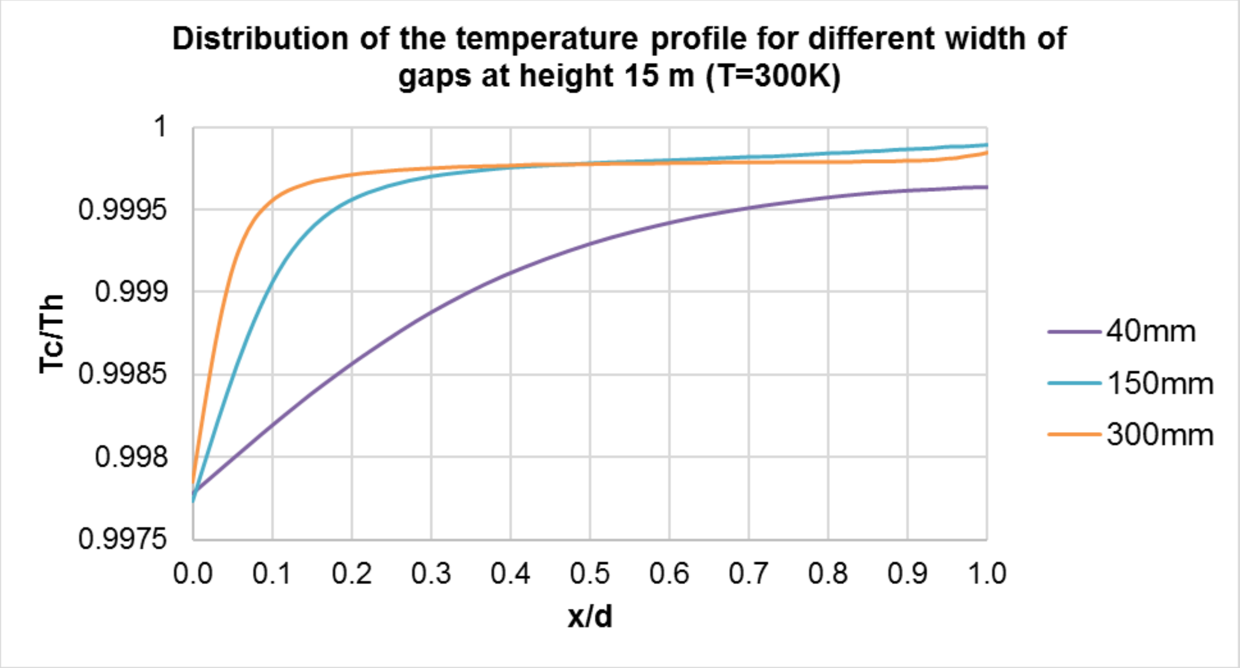

Figure 10. Distribution of the temperature profile for different width of gaps at height 15 m (T = 300 K)

Analyzing the velocity profiles in the gap, it can be said that regardless of the temperature difference for the gap of 40 mm, the highest velocity is observed. Observed a small difference between the velocity profiles for clearances 150 mm and 300 mm. the dependence for the two gaps are the same. However, the average over the cross section of the gap, the speed is less, if the clearance is wider.

The temperature profiles for the narrowest gap are more uniform because the average speed in the gap is higher. Temperature profiles for large gaps are similar and have a pronounced wall bend.

The constructed model has a number of advantages. The model takes into account the effect of gaps between tiles. The temperature on the surface of the building is determined by the solution of the conjugate heat transfer problem. The ambient temperature is set to be removed from the outer surface of the ventilated facade, which eliminates the influence of boundary conditions. The resulting model is an improvement of the model used in the article [29].

4. Conclusions

1. The air velocity in the ventilated gap depends on the time period in the year. In winter, the speed can be equal to that required, and in summer no convection will occur. Or in the summer it works optimally, and in winter there are too high speeds which do not meet the requirements of fire resistance design and boundary layer theory. Also at high temperatures the reverse air flow can occur.

2. Facade structure can be improved by adding additional elements. Since the motion is due to the temperature difference, it is possible, as an option, to add a heating element at the bottom of the structure. Then due to temperature difference is created artificially, the difference in air densities in the lower part of the building will be realized compared to the upper one in the ventilated gap. This method is suitable when motion does not occur, or air movement is from the top to down. Thus, the air will move in the direction in which it was originally provide for by design decisions (upward). Also an additional measure can be a fan, which will mechanically promote the development of the airflow movement vertically upwards.

3. The results of this research can help for determination the necessary thickness of the gap or take additional measures to increase the efficiency of the systems.

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