NUMERICAL SIMULATION OF DOUBLE SKIN FACADES IN WINTER CLIMATES

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ABSTRACT

The presented study reveals the analysis of the thermal behaviour of double skin facades (DSF) in winter conditions, using numerical simulation tools. The aim of the study is the development of a 3D simulation model, capable to evaluate the thermal behaviour of the modular elements in the DSF systems. This is essential requirement in the prediction and visualization of the facade's thermal behaviour in the design stage and in the assessment of the real behaviour of such facade, when the specified modular elements are changed by the customer.

The presented numerical simulation model aims to adequately reproduce the resulting set of thermal characteristics of the modular elements, to determine with sufficient accuracy their distribution in the real objects, implemented in the models in DSF systems. An algorithm is developed in the study and graphical visualization of three models of double facade systems with and without DSF are analysed under winter conditions, using data from a meteorological station located in North-Eastern Bulgaria. A software product was used to represent the processes of heat and mass transfer, in which the corresponding boundary and initial conditions were set, based on which the results and analyses were obtained. The use of such numerical modelling is effective enough to predict the expected thermal behaviour of DSF systems. Thus, when selecting a DSF facade system, awareness of the thermal behaviour is ensured, and the financial efficiency of the project is more easily determined. Such a customized approach not only improves the sustainability and efficiency of buildings, but also satisfies the unique preferences and requirements of the customers.

Keywords: DSF system, modular type, thermal behaviour, modelling, finite element method.

INTRODUCTION

In recent decades, the glass facades have become a dominant feature in the architectural design. Office buildings and other commercial buildings with such facades are being built in various parts of the world [1 - 4]. Their advantages include natural light, visual appeal, and quick installation [4]. Despite these positive aspects, they also raise questions about their energy efficiency [5]. However, the energy efficiency of glass facades, also called glazed facades, seems to be a poorly researched area. Some believe that glass facades cannot be as energy efficient as traditional walls. This is due both to the high energy costs associated with heating and cooling glass buildings, and to the fact that high-quality glass facades are considered expensive to build and maintain [6 - 8].

The current interest in energy-efficient buildings is driven by the environmental challenges and the rise of energy costs [9]. This directs the attention of the construction industry towards reducing energy needs and carbon emissions. Buildings use a significant amount of energy and materials and are also a significant source of carbon emissions on a global scale. The growing interest in energy efficiency in buildings is fully justified, as this aspect plays a key role in reducing carbon emissions, which are a major factor in climate change [10 - 14]. The office buildings, with their diverse technology, solar gains and pursuit of comfort, occupy a leading position in high energy consumption, which necessitates the need for more efficient heating and cooling systems. The structure of building walls is of great importance for optimizing thermal comfort conditions and reducing energy needs [15 - 18].

On the other hand, building energy modelling is a tool that enables the prediction of building energy requirements through computer simulations, that consider multiple factors, including the thermal insulation characteristics of the building envelope, building orientation, solar radiation, climate data, and more [19]. Fig. 1 shows a typical plan for a middle floor and a section of a DSF system. This plan and section clearly demonstrate the placement of the modular elements and the structure of the building, emphasizing the importance of DSF for the thermal insulation and energy efficiency of the building. They are a key element in DSF thermal behaviour analysis and system optimization.

DSF facades represent a variety of types, including different combinations of glass, insulation materials and ventilation systems used in the building. These diverse configurations enable customized solutions that combine visual appeal with high energy efficiency and building sustainability. DSF facade types are shown in Fig. 2.

The configuration of the box-type window facade, shown in Fig. 3, is extremely suitable in cases where a high level of acoustic comfort is required and when it is necessary to limit the penetration of external noise into the interior of the building. Such a configuration can be specially designed to ensure minimal sound transmission between adjacent rooms, providing satisfactory working and living conditions in the building.

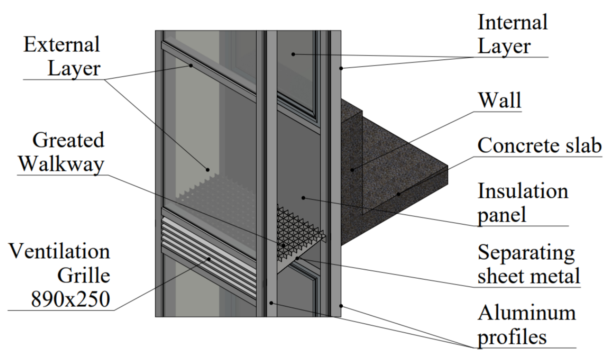


Fig. 1. A typical middle floor plan and section from DSF.

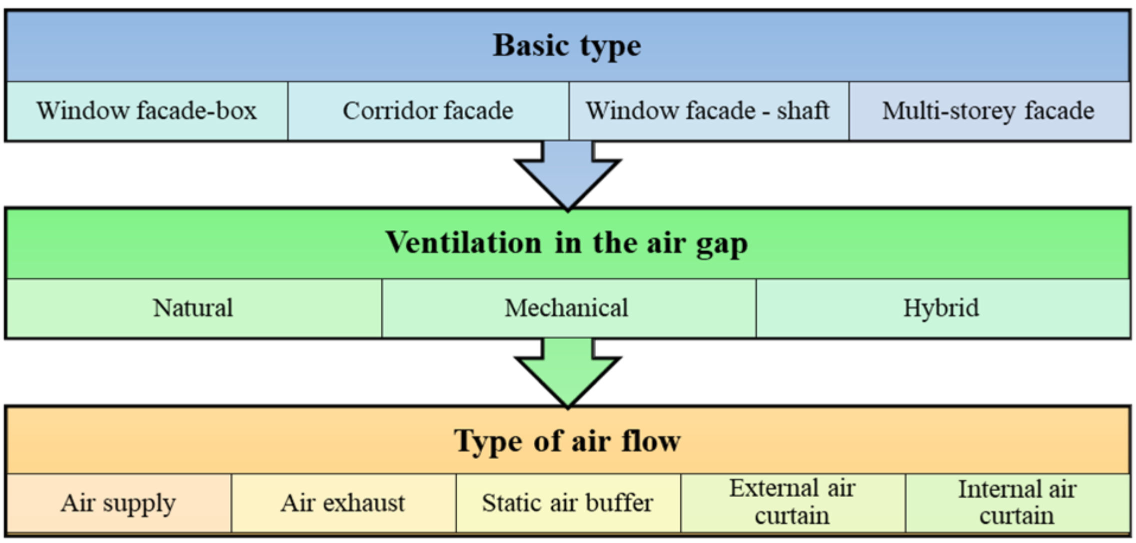


Fig. 2. Types of DSF facades.

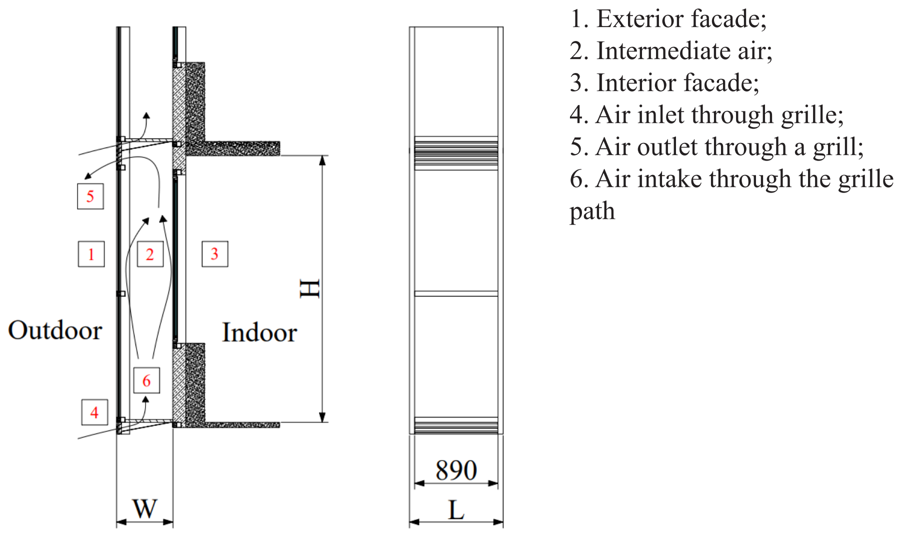


Fig. 3. Section of window facade - box type.

In this paper, a computer model has been developed, and an evaluation of the energy thermal behaviour of the modular elements of the DSF facade system has been carried out. The aim is to visualize the thermal insulation behaviour and provide an opportunity to evaluate the real behaviour under different thermal behaviour of the modular elements specified by the client.

EXPERIMENTAL

Methodology and modelling

The simulation modelling of DSF facade systems and the evaluation of the thermal behaviour of the modular elements specified by the client include the development of an algorithm. This algorithm allows changing input parameters such as the population location, characteristics of the modular element, environmental parameters, etc.

Setting up of the external environment parameters

The input data for the numerical simulation are the outdoor air temperature, air relative humidity, wind speed and direction obtained on a typical winter day from meteorological data, with the meteorological station located in North-Eastern Bulgaria. Modelling was done over a period of 24 h, on a winter cloudless day, to determine the solar radiation in a clear atmosphere. The virtual camera is available during the working day between 8 a.m. and 6 p.m.

The development of an algorithm for simulation modelling of facade systems DSF is one of the most promising technical solutions applied to building facades, which allows control of the energy characteristics of buildings through computer modelling with parameters set by the customer. DSF can be defined as "a special type of envelope where a second cell, usually transparent glazing, is placed at the front of an ordinary building facade". The air cavity between these two "cells" (glasses) is 0.6 m and 0.9 m wide. Simulation modelling is important for solving such type of tasks related to the thermal and energy efficiency of DSF and allows by varying the input parameters to solve the task. Solving the task is also related to the modelling of heat and mass exchange processes in the environment of a suitable software product and includes the development of an algorithm shown in Fig. 4.

The simulation modelling is carried out using equations from (1) to (6) which are integrated in a software product [20].

The mathematical model of the Double-Skin Facades involves the solution of heat transfer and fluid dynamics equations. To describe these conditions with differential equations, there are used the fundamental equations of fluid mechanics (the Navier-Stokes equation) and the heat transfer equation for the corresponding heat conduction.

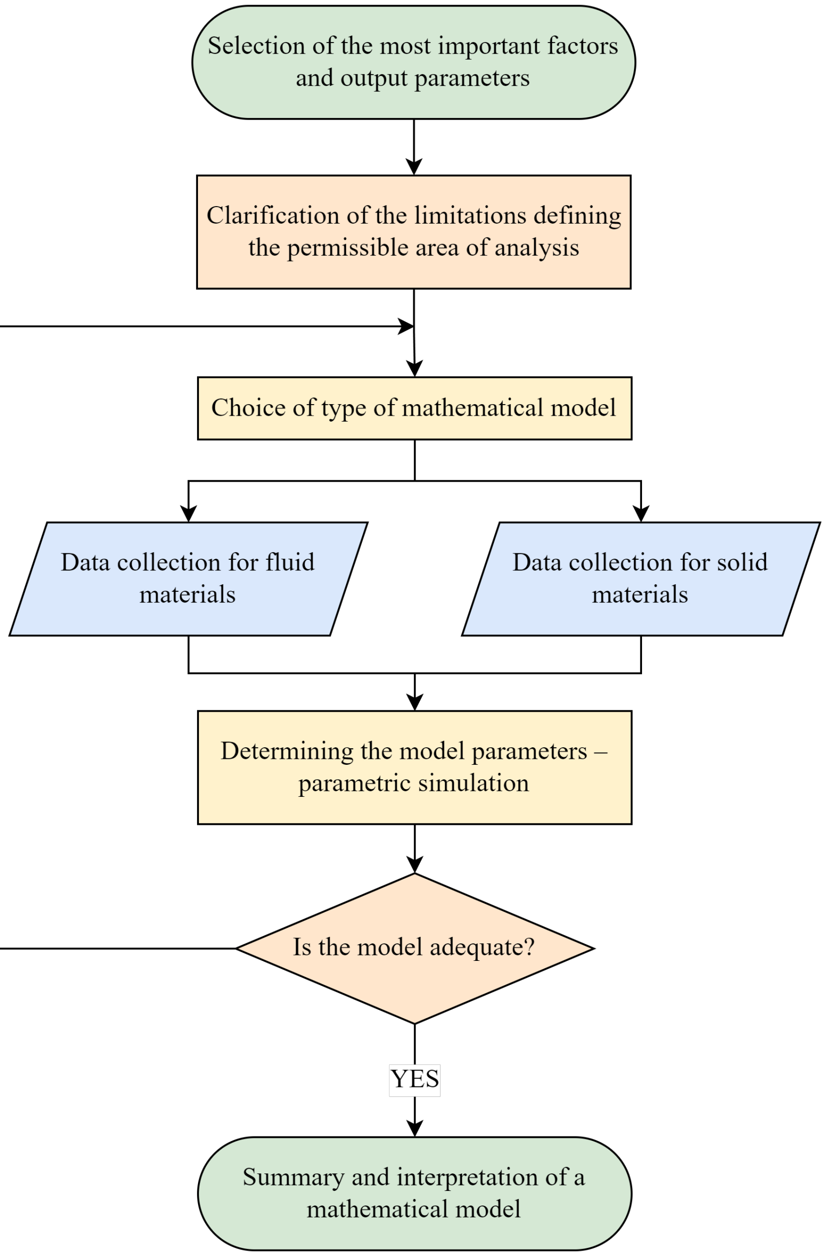


Fig. 4. Algorithm for solving the task with a suitable software product.

The Navier-Stokes equation for incompressible flow:

$$\rho\left(\frac{\partial \vec{v}}{\partial t}+(\vec{v}\cdot\nabla)\vec{v}\right)=-\nabla p+\mu\nabla^2\vec{v}+\rho\vec{g} \qquad (1)$$

The Continuity equation for incompressible flow:

$$\nabla\cdot\vec{v}=0 \qquad (2)$$

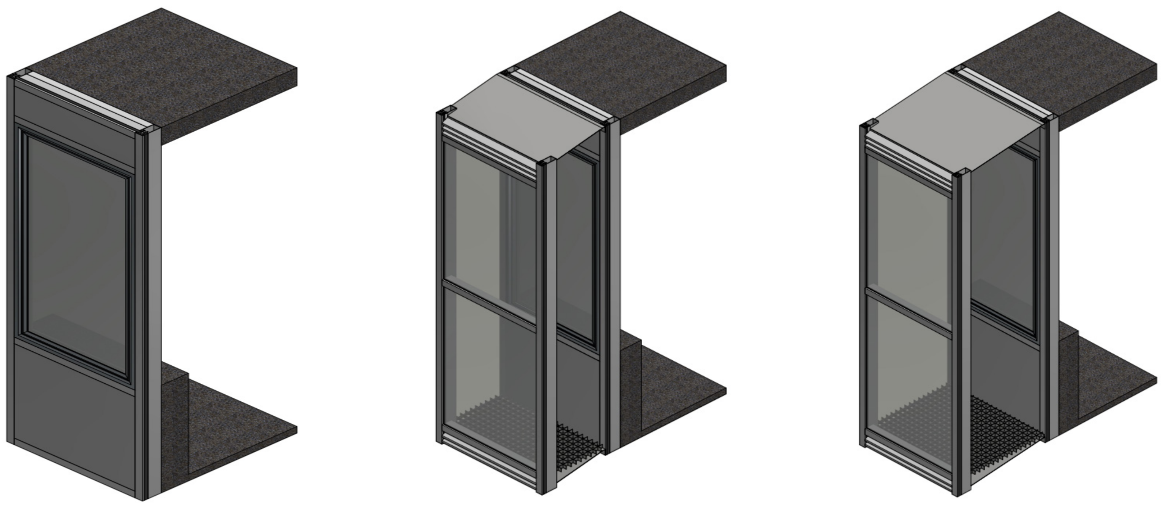
Heat transfer equation (energy equation):

$$\rho C_p\left(\frac{\partial T}{\partial t}+\vec{v}\cdot\nabla T\right)=k\nabla^2 T+q_V \qquad (3)$$

where: ρ - density, kg m^{-3}; $\vec{v}$ - velocity vector, m s^{-1}; t - time, s; p - pressure, Pa; μ - dynamic viscosity, Pa s; $\vec{g}$ - gravitational acceleration vector, m s^{-2}; C_p - constant

Table 1. Thermophysical properties of materials for elements of window systems.

Material	k, W m^{-1} K^{-1}	ρ, kg m^{-3}	C_p, J kg^{-1} K^{-1}	ε
Concrete	1.1	2306	837	0.92
Aluminum	180	2700	896	0.2
Rubber	0.7	1700	700	0.9
Steel	53	7833	465	0.3
Glass	0.78	2700	840	0.92
Isolation	0.035	25	1400	0.8
Argon	0.0179	1.63	520	-
Air	0.02563	1.205	1004	-



a) FS without DSF b) FS DSF 0.6 c) FS DSF 0.9

Fig. 5. Geometric objects.

pressure specific heat, J kg^{-1} K^{-1}, T - temperature, K; k - thermal conductivity, W m^{-1} K^{-1}; q_V - volumetric heat source, W m^{-3}.

Physical conditions

The physical conditions include the thermophysical properties of solid materials and the gas medium, and the viscosity of gases as a function of temperature or as constants shown in Table. 1.

Geometry of the studied objects

The studied object shown in Fig. 5 was designed and built digitally in a virtual environment using the software product "Autodesk Inventor Professional" [21], and then studied in another fluid and thermal analysis environment "Autodesk CFD" [20]. Three models were built using the finite element method. The first model includes a simple facade system (FS without DSF), the second is a double box facade system with an air layer distance of 0.6 m (FS DSF 0.6) and the third is a double box facade system with an air layer distance of 0.9 m (FS DSF 0.9). The dimensions of the three types of models used in this model are like the existing experimental facade systems and are given in Table. 2. Approximations are made on the entire construction of the facade system. The frame on which the facade system is placed is built as separate elements, and the seals as a monolithic object. The bolt assemblies and structural elements when attached to the building were neglected, because do not strongly influence the

Table 2. Dimensions of facade wall types.

Facade type	FS without DSF	FS DSF 0.6	FS DSF 0.9
Length, m	2.139	2.739	3.039
Width, m	1.0	1.0	1.0
Hight, m	3.0	3.0	3.0
Thickness of the air layer, m	0.0	0.6	0.9

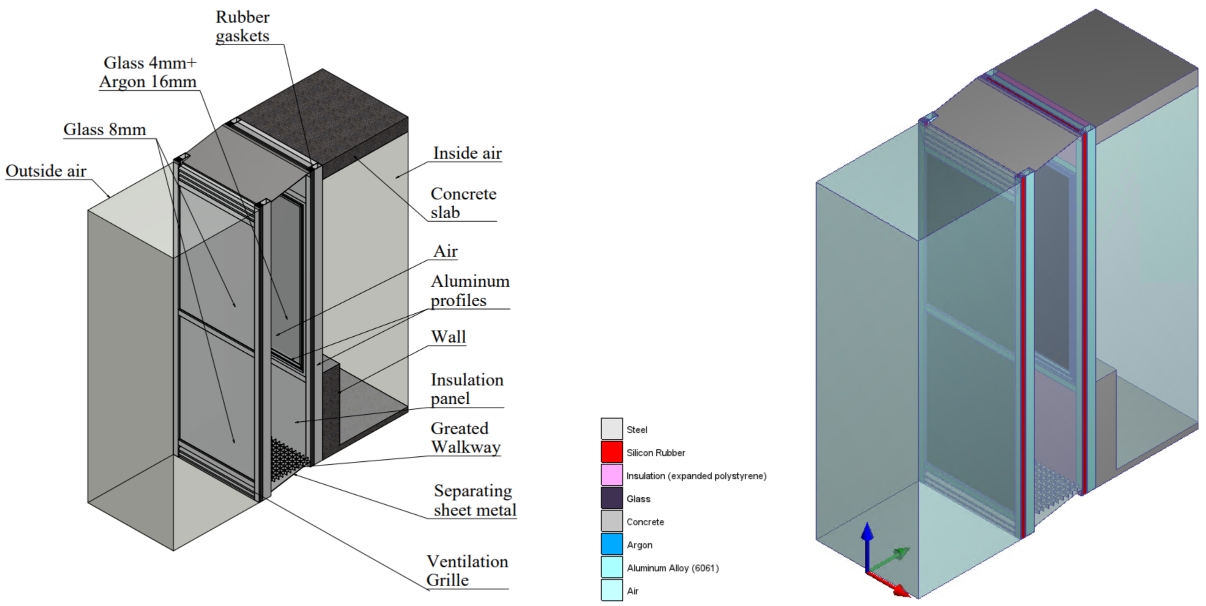


Fig. 6. Scheme of the studied object, with specified materials.

processes that conduct in the considered spaces. The same idealization has been done with the external cladding aluminum profiles of the facade system. The geometry of the models and the location of the samples is presented in Fig. 5.

Specifying the materials with physical characteristics

After the study of the materials from which the facade construction was built, regarding their thermophysical characteristics, a new library was built in the "Autodesk CFD" software product. For materials for which there is no information in the literature regarding thermophysical characteristics, their constant values under normal conditions are assumed. Fig. 6 presents the object under consideration, with the specified materials from which it was built.

Boundary Conditions

Velocity is a vector quantity and has x-axis, y-axis, and z-axis components. Thus, for the case where the air enters along the y-axis:

- Ambient Air Velocity - $\vec{v}|_{A_{air\_out}} = (0, 4.00, 0)\ m\ s^{-1}$;
- Speed of the air inside the room - $\vec{v}|_{A_{air\_in}} = (0, -0.25, 0)\ m\ s^{-1}$.

The pressure acting inside the room and in the environment is assumed to be barometric - $p_b|_{A_{air\_out(in)}} = 101325\ Pa$;

The ambient temperature is set according to the region under consideration. The temperature inside the room is set according to the current regulations of the country for the winter season:

- Ambient air temperature - $T|_{A_{air\_out}} = -11°C$;

- Air temperature inside the room - $T|_{A_{air\_in}} = 22°C$.

Boundary conditions in the natural state model mark the continuation of the geometric model as surface temperature and heat flux ($T = 0\ and\ q = 0$ for $A_{out(in)}$).

A type I boundary condition is set with air velocity inside and outside, which is constant for the whole period of the analysis, shown in Fig. 7 with a black bar.

A boundary condition of type I is set with the air temperature, which is a constant temperature of the ambient air and the air in the room for the entire period of the analysis, shown in Fig. 7 with a bluish-green band.

A boundary condition of type I with a manometric pressure of 0 Pa of the surrounding air is set, by which the direction of movement of the fluid and heat flows, shown in Fig. 7 with an orange bar, is set.

A boundary condition is set to separate the type of facade and its surfaces that contact the upper and lower floors, shown in Fig. 7 with a red bar.

Discretization of the studied building facades

Discretization of the assembly represents an approximation of the system of prismatic elements, which are divided into solid and fluid for the three considered cases. The setting of the discretization is with the parameters presented in Table 3 and Fig. 8a, b and c.

RESULTS AND DISCUSSION

The solution of the FS without DSF problem is set for 300 iterations, but upon reaching 10 approximate values with a solution deviation of 4 decimal places, the program stops the calculation. The same was done for the other two regimes, which are presented in the Table. 4 with the assumed parameters and the machine time to solve the problems for the three experiments.

Fig. 8a, b and c show the results for temperature and velocity fields of building facades obtained in iteration 200 for building facades with and without DSF. The presented solutions provide a visual quantitative representation of the temperature fields and the air velocity inside and outside the room, as well as in the intermediate space in the three (a, b and c) simulations.

On Figs. 9 and 10 are presented the temperature fields and velocity vectors.

From Fig. 10 a, b, and c a temperature cloud forms from vectors with a constant temperature and uniform heating of the internal surfaces. The resulting velocity clouds are: 4.0 m s^{-1} at FS without DSF, 1.4 to 1.7 m s^{-1} in the intermediate space of FS DSF 0.6 and FS DSF 0.9. An uneven temperature field along the building height and facade structure is observed due to air movement on both sides of the enclosing surfaces and convection outside the facade, in the intermediate space, and inside the room.

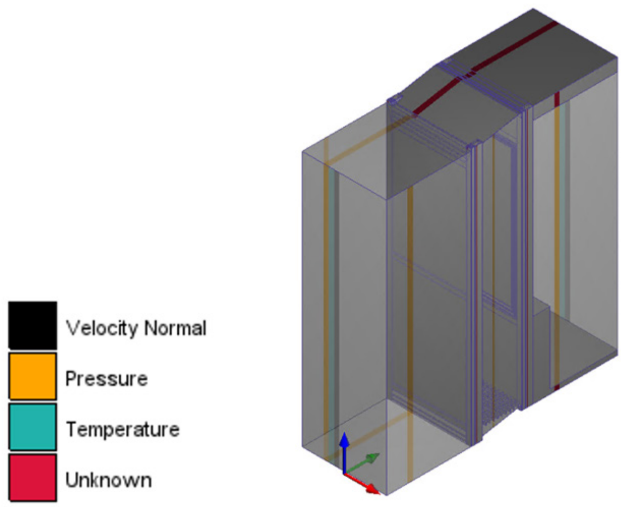
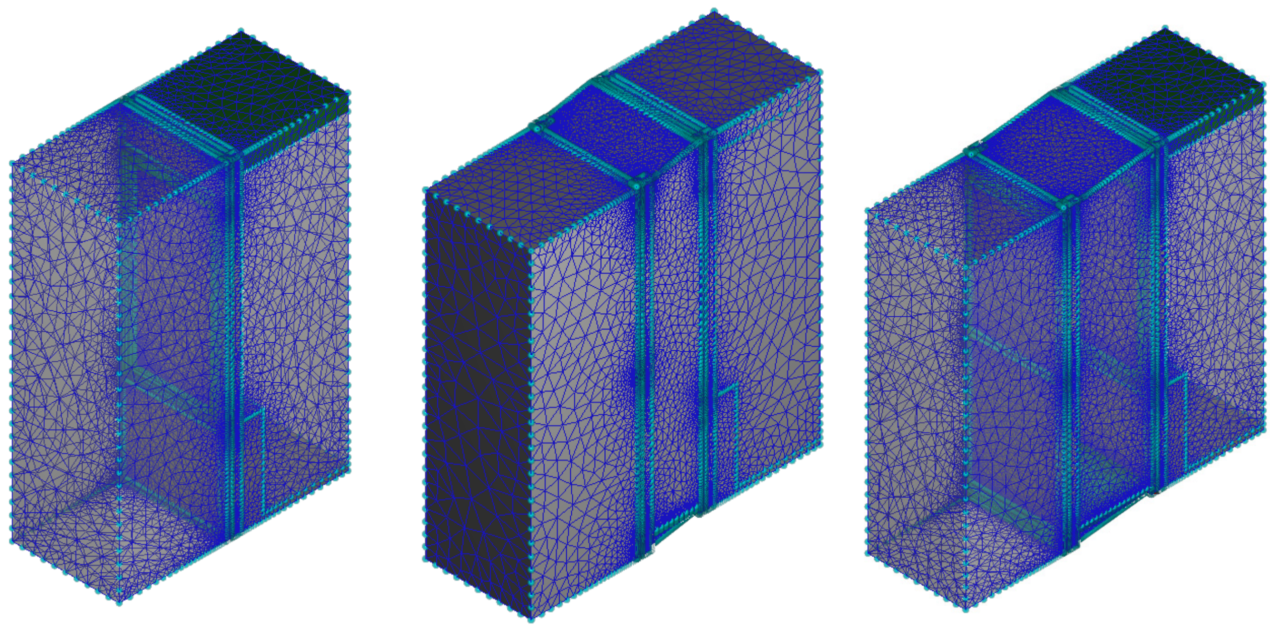


Fig. 7. Surfaces with set boundary conditions for ambient air temperature and pressure.

Table 3. Input and output data of the discretization.

Input data	Value
Resolution factor	1.0
Edge growth rate	1.1
Minimum edge points	2
Points on the longest edge	10
Bounded surfaces ratio	20
Number of layers	3
Layer coefficient	0.45
Output data	Quantity
Total number of nodes FS without DSF	269 360
Total number of elements FS without DSF	961 928
Total number of nodes FS DSF 0.6 m	761 462
Total number of elements FS DSF 0.6 m	2 784 699
Total number of nodes FS DSF 0.9 m	826 887
Total number of elements FS DSF 0.9 m	3 039 574



a) FS without DSF b) FS DSF 0.6 c) FS DSF 0.9

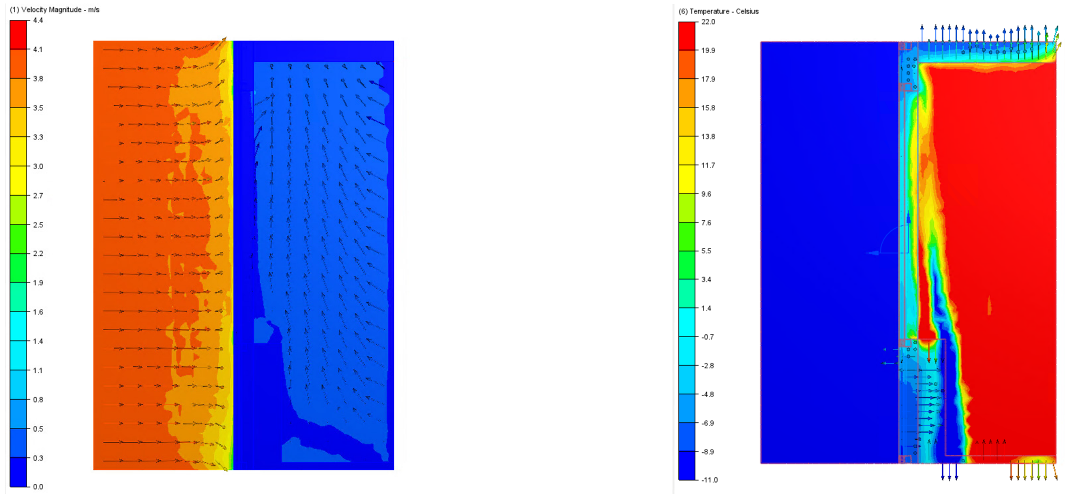
Fig. 8. Discretized view of the investigated facade systems.

Table 4. Set up of the solution steps and solution time.

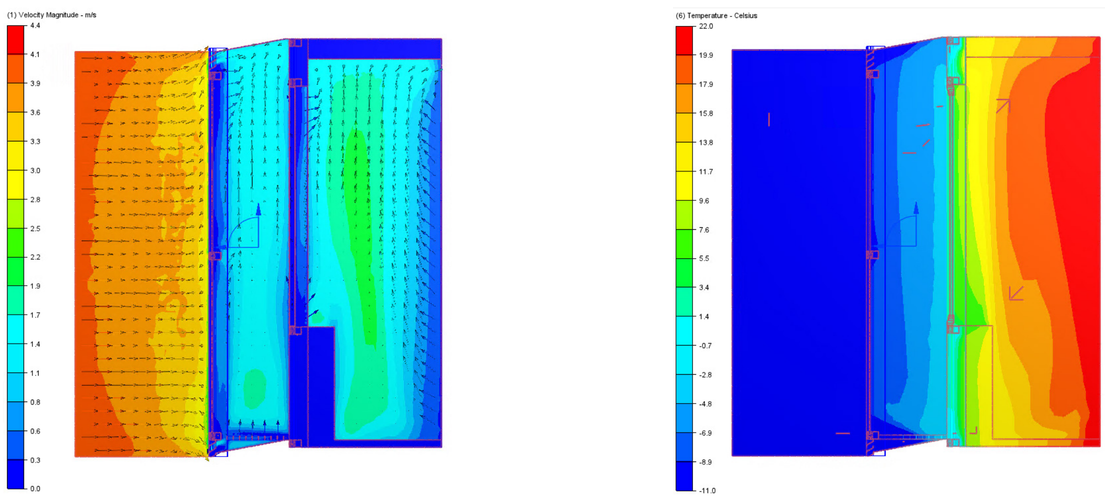
Solution mode	Steady state
Solution type	Fluid and thermal
Turbulence model	k-ε
Iterations for calculation for FS without DSF	242
Iterations for calculation for FS DSF 0.6 m	251
Iterations for calculation for FS DSF 0.9 m	244
Solution time for FS without DSF	2527s ≈ 42min
Solution time for FS DSF 0.6 m	7854s ≈ 2h 11min
Solution time for FS DSF 0.9 m	9802s ≈ 2h 43min

Based on the presented simulations and analyses, results are obtained that show how the DSF facade system can be optimized to achieve higher energy efficiency. The present study shows that double-skinned facades significantly improve the thermal behaviour of buildings in winter conditions, by reducing the air velocity in the intermediate space and by improving the temperature distribution. These results coincide with the research of Johnson et al., who also found a significant reduction in the heat losses and improvement in the occupant thermal comfort, when using DSF facades in different climates [22].

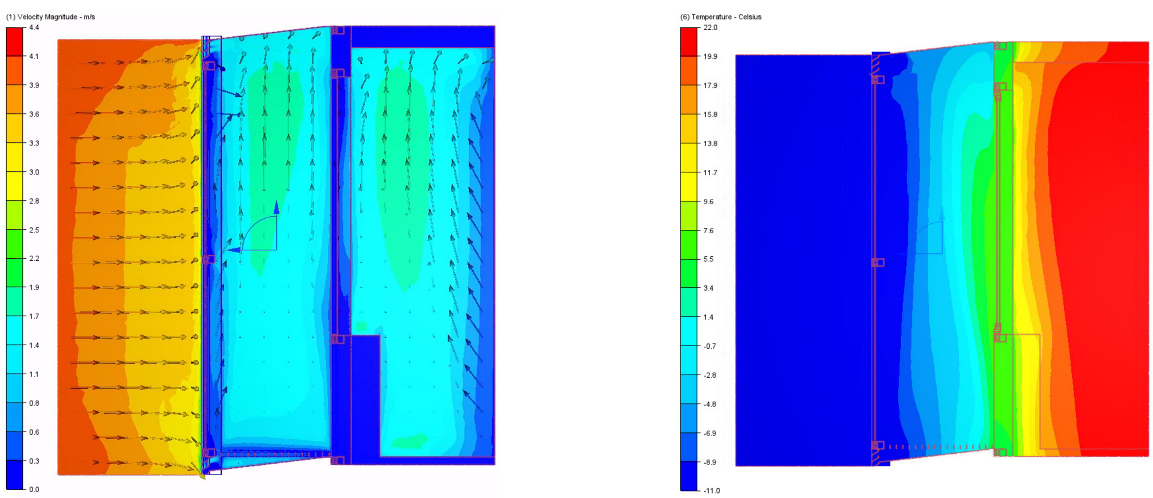
The research analysis also confirms the results obtained by other authors that double-skinned facades significantly improve the thermal efficiency and energy balance of the buildings. The reduction of air velocity in the intermediate space and a more even temperature distribution are major benefits, that are confirmed by numerous studies. Regardless of the differences in climatic conditions and simulation methods, the conclusions about the benefits of DSF facades are similar and highlight their importance for sustainable and energy efficient constructions.



a) FS without DSF



b) FS DSF 0.6



c) FS DFS 0.9

Fig. 9. Velocity and temperature fields in sections of the YZ plane.

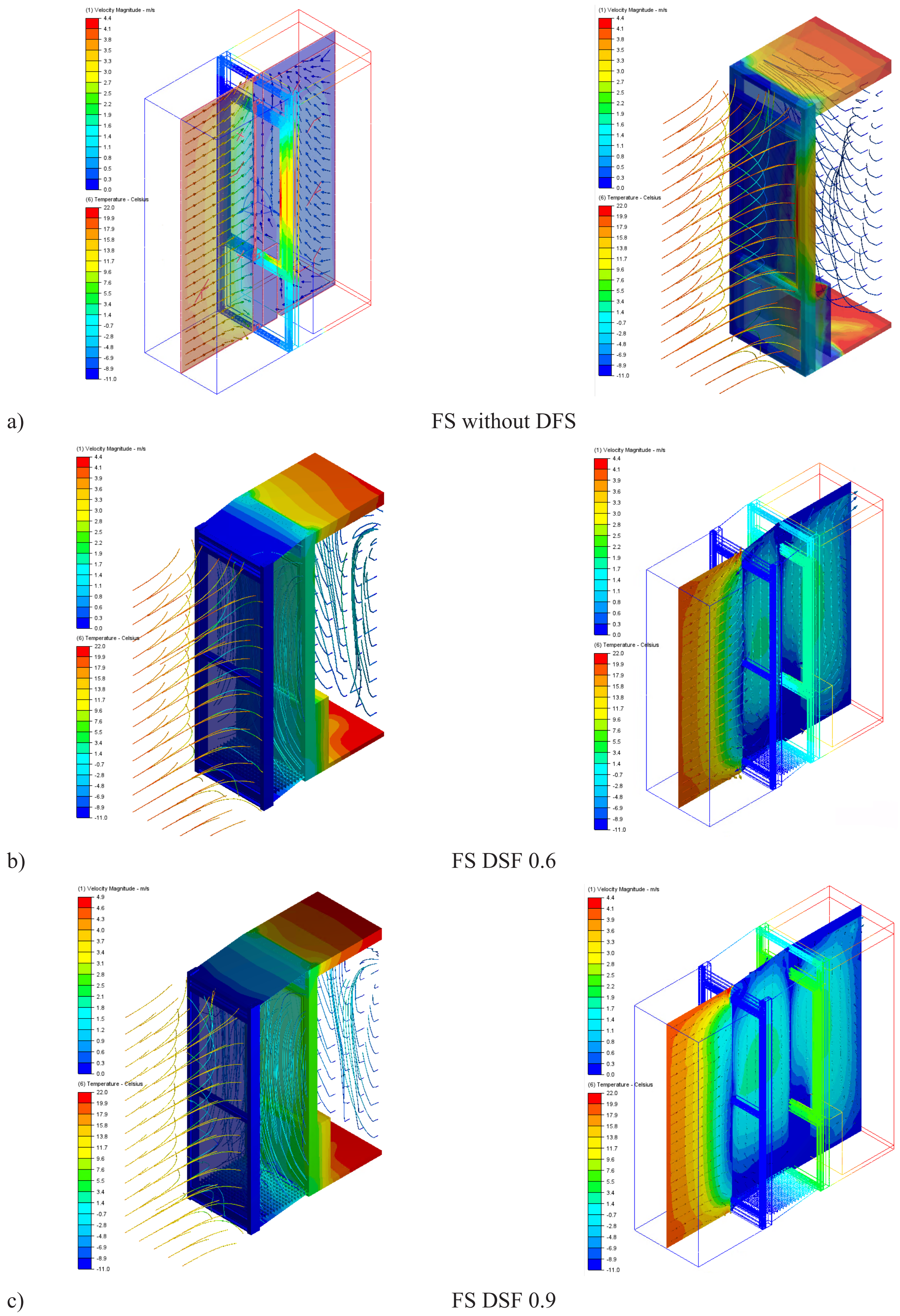


Fig. 10. Temperature fields and velocity vectors.

CONCLUSIONS

The presented study analyses the thermal behaviour of DSF facades under winter conditions, conducted through numerical simulations. Three facade variants were studied: facade without DSF, facade with DSF 0.6 and facade with DSF 0.9. The results show that DSF systems significantly reduce the air velocity in the intermediate space, which improves the buildings thermal insulation and temperature distribution. The facades with DSF 0.6 and 0.9 have lower air velocities (1.4 and 1.7 m s^{-1}) compared to the facade without DSF (4.0 m s^{-1}). The increased calculation time in the DSF simulations proves the more complex thermodynamic processes but leads to more accurate results. It was proved that DSF facades significantly reduce heat losses and improve the energy efficiency of buildings. The study highlights the importance of optimizing facade systems for sustainable constructions. The application of DSF facade systems can lead to significant energy savings and improved comfort in buildings. In conclusion, the study clearly demonstrates the potential of DSF facades to significantly improve the energy efficiency and sustainability of buildings.

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