ENERGY BALANCE OF SMART VENTILATED FACADE

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Abstract
This article explains the function and basic energy balance for a smart facade system that is being researched at Brno University of Technology. This system is an upgrade to an already well-known ventilated facade. The upgrade is mainly presented by efficient control over built-in shut-off dampers inside the ventilated gap. The main goal is to reduce the energy consumption of buildings and create a healthy and comfortable indoor thermal microclimate in a much more ecological way. Numerical calculations are being used to present the energy use of a given facade in comparison with other conventional facade systems on the same building with identical boundary conditions. FSVM software which provides these calculations has been developed by the same research team. It can calculate the energy balance of conventional facades, ETICS and prototype of smart facades as well. This article presents ongoing research and results of the simulation of the heat flow of these three main facade systems throughout the year. Significant variables for facade heat flow calculations are weather and outdoor boundary conditions. They are used in this article as conditions for the Czech Republic which has a mild climate and four different seasons of the year.

Keywords
Ventilated facade, smart facade, energy balance, ventilated gap, numerical simulation

1 INTRODUCTION

A smart facade is a newly developed system for a building envelope. The main goal of the project was to use positive thermal-technical properties of two main conventional facade systems – ETICS (external thermal insulation composite system) and ventilated facade in one facility. The main goal is to effectively reduce the energy consumption of the building on heating and cooling of the interior without further or excessive energy needed to operate the system itself.

The function of the ventilated facade has been described in many articles. Some are important for defining thermofluidic dynamics [1] which is the key to understanding the facade's main function. A positive attribute of the ventilated facade is the ability to drain moisture from the perimeter shell and the possibility to ventilate air heated by solar irradiation, which is very useful in environments or seasons with high daily solar irradiation of buildings. This reduces the energy needed for cooling the indoor microclimate [2].

The ETICS system has on the other hand shown good performance when conserving thermal energy from inside of the building [3]. The heat flux from interior to exterior in simulation has shown lower absolute values than the ventilated facade in the winter season when a building interior needs heating.

The innovative design of a smart facade, developed at the Institute of Building Services, Faculty of Civil Engineering, Brno University of Technology, involves a dynamic system capable of modulating airflow within its cavity. This is achieved through a combination of forced ventilation mechanisms and adjustable flaps located at the intake and exhaust openings which respond adaptively to varying external boundary conditions. Ventilation fans, integrated into the facade, are responsible for enhancing airflow, thereby efficiently dissipating increased thermal loads. The system incorporates shut-off dampers that control the airflow, thereby regulating the temperature within the ventilated cavity. These flaps operate in two distinct states: "open" and "closed". However, the potential for multi-stage control of these flaps is currently deemed non-essential, given the presence of leakages in the external shell or cladding. These leakages, which allow air to inadvertently escape from the cavity, can range from 10% to 40%, contingent upon the cladding's design and the dimensions of the interspaces among the individual cassettes [3].

The FSVM software, an acronym for "Facade with Ventilated Gap" in the Czech language, also a product of our faculty, facilitates the analysis of heat transfer through the ventilated facade and temperature regulation within a specified facade system. This tool enables the calculation of the heat transfer coefficient for perimeter wall constructions incorporating a ventilated facade. It does so by considering various input parameters of the facade,

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including the thermal bridging effects caused by the anchors of the external cladding. This functionality is also accessible in the software's free version [4]. Additionally, the FSVM predicts facade performance on an hourly basis throughout the year, accounting for interior temperature adjustments and the impact of climatic variations, including the substantial effect of solar declination and solar radiation heat gains over the year.

A particularly valuable feature of the FSVM is its capability to simulate heat flows across different months for a given ventilated facade, a corresponding virtual ETICS system (for comparative analysis), and the smart facade. This enables the software to demonstrate the percentage reduction in heat flows achievable through the use of a smart facade. The FSVM software's calculations have undergone extensive verification and refinement as part of the project funded by TACR (abbreviation for Technological Agency of the Czech Republic) FW03010062: Smart facade with optimized energy properties [3].

One of the most important objectives within our smart facade research endeavours is to enable the prediction of the structural-physical behaviour within the facade, contingent upon quantifiable boundary conditions. This ambition is gradually being realized, and a tangible outcome of this research results in the continuous evolution of our FSVM software. The latest, yet-to-be-published iteration of this software is now capable of responding to simulated behaviours within the system. It optimizes the conditions inside the perimeter wall structure equipped with a ventilated facade. This optimization is primarily achieved through the regulation of shut-off dampers. By precisely controlling these dampers, we can minimize heat flow through the facade structure, thereby facilitating substantial energy savings [3].

2 METHODOLOGY

Calculating energy balance the way scientists and engineers already know, differs from calculating balance for the ETICS and ventilated facades. A stationary approach is used for the ETICS and a non-stationary approach for the ventilated facade.

In the stationary approach for the ETICS we need to know the temperature of the interior and the temperature difference between the interior and the exterior surfaces of the facade, determine the overall heat transfer coefficient of the structure and convection heat transfer coefficients of the interior and exterior surfaces of the facade.

The non-stationary solution used for calculating energy balance for ventilated facade uses a similar approach, only more things need to be considered. The corrected heat transfer coefficient of the facade need to be solved (see below) and four convection heat transfer coefficients: coefficient on both exterior and interior side of facade cladding, coefficient on wall surface in air gap and coefficient from building interior, need to be determined. The next step is determining the equivalent solar temperature on the outer cladding surface. The airflow volume of air inside the gap can be set by knowing the wind area value for the current region and by the air pressure difference from the bottom inlet to the top outlet of the facade. The air temperature inside the gap can be subsequently determined. Knowing this, the heat flow between the interior and ventilated gap and the heat flow between the gap and exterior through the cladding can be told. Based on these heat flow values the energy balance of the ventilated façade can be determined. The basic calculations follow the procedures and relationships according to the standard [5].

The corrected heat transfer coefficient needs to be set since the connection of the facade to the perimeter wall creates a thermal bridge that can have an impact on heat flux [6]. From the perspective of having sufficient thermal insulation, the anchor holding the outer cladding is weakening the insulation effect of the wall composition. The corrected heat transfer coefficient was calculated according to the European standard [7]. The calculations used the three-dimensional thermal field for the point heat transfer coefficient. Visualization of the results are shown in Fig. 1.

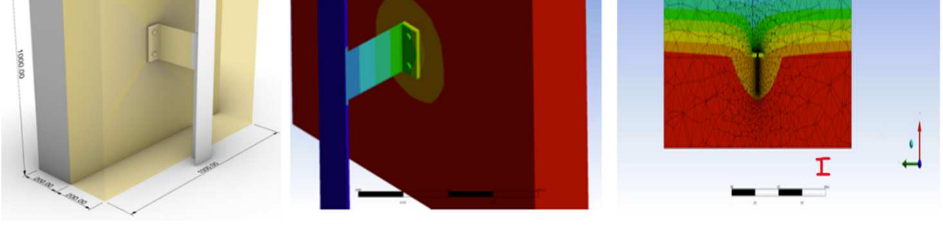

Fig. 1 Visualization of the point heat transfer of the wall anchor

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Research has shown that the surface temperature of the cladding can already be predicted with little error by using the following formula:

$$t_p = t_e + \frac{I \cdot \varepsilon}{\alpha} \tag{1}$$

Relation (1) computes t_p which is the surface temperature of the cladding in °C. t_e is the temperature of an outdoor air in °C. Input value I represents the intensity of solar radiation in $W \cdot m^{-2}$. The two coefficients ε – coefficient of light absorption of the cladding without unit and α – thermal transmittance coefficient in $W \cdot m^{-2} \cdot K^{-1}$ are coefficients which were a part of approximation research from measured data on real facades. They are expected to be different for different months. To be physically correct, they are different for each different boundary conditions. Simply said in this case – they are different with each outdoor condition difference.

The outdoor air temperature and the intensity of solar radiation on the real facade in real time can be measured. Two coefficients ε and α must be set and they are considered constant for one calendar month for a single type of cladding. Changing two boundary conditions – calendar month and cladding type – changes these two coefficients. Further research on this method is described in an article [3].

Calculating the energy balance for a smart facade is similar to the non-stationary solution used for the energy balance of a conventional ventilated facade. The FSVM software developed at our institute isused for these calculations [4]. The calculations are thoroughly described in an article from the head researchers of this project [8].

The calculation procedure follows:

- height of sun and its azimuth,
- numerical expression of the angle between the normal of the illuminated surface and the direction of the sun's rays for a vertical wall,
- direct incident solar radiation in the direction of the sun's rays, diffuse incident solar radiation, direct incident solar radiation on an azimuthally oriented wall and from these the total incident solar radiation on an azimuthally oriented wall,
- equivalent solar temperature on an azimuthally oriented wall,
- corrected ε and α coefficients [3],
- outer cladding surface temperature on an azimuthally oriented wall [3],
- variable convection heat transfer coefficient for free airflow and its heat transfer coefficient of outer cladding when it varies,
- heat gain from the total radiation over a facade width of 1 meter for a given total facade height,
- wind speed around the facade depending on wind map region value,
- outlet air temperature in the gap between the cladding and wall insulation,
- heat flow from the interior to the ventilated gap considering corrected heat transfer coefficient for the whole height of the facade and 1-meter width with considering heat absorption of used materials,
- yearly thermal balance for the whole height of the facade and 1-meter width calculated for every hour shown by monthly overview.

The FSVM software [4] shows values of detailed heat flow in kWh/month, its recommendations on shut-off dampers setting for optimal performance on the side of energy balance, more precisely, the lowest heat flows possible and heat flow comparison with conventional facade systems. The idealized model of a smart facade shows 0 W of heat flow between the interior and the exterior for every month.

3 DATA

Data for the FSVM optimization and simulation capabilities with insignificant error has been gathered on several real ventilated facades around the Czech Republic in the years 2020-2023. Measurement on data logger AHLBORN ALMEMO 5690-2 and a series of temperature sensors gave us some data for every 10 minutes 24 hours a day for several control points. More detail on data gathering can be found in an article [3].

The free version of the FSVM software has built-in input values of the default ventilated facade for presentation. The input values are listed in Tab. 1.

Tab. 1 Input parameters for default facade in the FSVM software.

Parameter	**Value**
Wall surface	100 m^2
Wall openings	20 m^2
Cladding type	Medium-heavy (up to 40 kg·m^{-2})
Bearing material	Steel
Pad thickness	10 mm
Winter exterior air temperature	-12 °C
Winter interior air temperature (t_{iz})	20 °C
Facade location latitude (lat)	50 °
Facade location longitude (long)	16 °
Facade location altitude (H)	300 m AMSL
Facade angle with a horizontal plane (α)	90 °
Facade azimuth (γ)	120 °
Mean calculated facade width ($\check{s}$)	1 m
Facade height (h)	15 m
Facade height above ground (h_0)	1 m
Mean calculated facade height (h_x)	7.5 m (temperature in the centre of the facade)
Bottom inlet coefficient	0.4
Upper outlet coefficient	0.6
Ventilated gap depth (d_m)	0.12 m
Parameter	Value
Narrowing of the intake vent (Z)	80%
Narrowing of the exhaust vent (Z_0)	70%
Czech wind map area (O)	2
Orthography (o)	City
Solar constant (I)	1,370 W·m^{-2}
Atmospheric pollution (z)	4 (throughout the year)
Temperature fluctuations amplitude (A_m)	7 K
Summer interior air temperature (t_{il})	25 °C
Air density (ρ_w)	1.2 kg.m^{-3}
Specific heat capacity of air (c_w)	1,010 J.kg^{-1}·K^{-1}
Closing flap settings	Oct-Mar closed; Apr-Sep opened
Cladding thickness (d_p)	0.08 m
Thermal conductivity of cladding (λ_p)	0.115 W.m^{-1}·K^{-1}
Relative solar absorptivity (ε_p)	0.7
Default convection heat transfer coefficient of outer cladding surface (α_e)	20 W.m^{-2}·K^{-1}
Air permeability of the cladding (n_p)	20%

Tab. 2 Default perimeter wall composition.

No. of layer	**Material**	**d [m]**	**λ [W.m^{-1}.K^{-1}]**
1	Thermal insulation	0.060	0.037
2	Bearing wall structure	0.380	0.111
3	Interior plaster	0.005	0.880

In **Chyba! Nenalezen zdroj odkazů.** there is d as a layer thickness in meters and λ as a coefficient of thermal conductivity of the material of the layer in W.m^{-1}.K^{-1}.

Possible graphic and numerical outputs from the FSVM software as of 03/11/2023:

- diffuse solar radiation,
- direct solar radiation falling on the facade,

- total solar radiation falling on the facade,
- equivalent solar temperature on the azimuth-oriented facade,
- outdoor temperature according to the season,
- corrected interior temperature according to the season,
- the temperature of the outer surface of the facade cladding,
- heat gain from total solar radiation on the facade,
- air temperature in the ventilated gap for the facade height *h*,
- air temperature in the ventilated gap for the selected height on the facade h_x,
- heat flux from the building into the air gap with opened shut-off flaps,
- heat flux from the building to the air gap with smart ventilation control,
- heat flux from the building to the exterior without a ventilated gap (virtual ETICS).

Expressing the reduction of heat flux through a smart facade in relation to a conventional ventilated facade in stationary and dynamic modes of calculation.

4 RESULTS

The issue with the thermal bridge of the wall anchor holding the facade cladding was partially eliminated using a plastic washer that is placed between the supporting wall and the L-shaped anchor. The plastic washer has higher thermal resistance than the anchor itself.

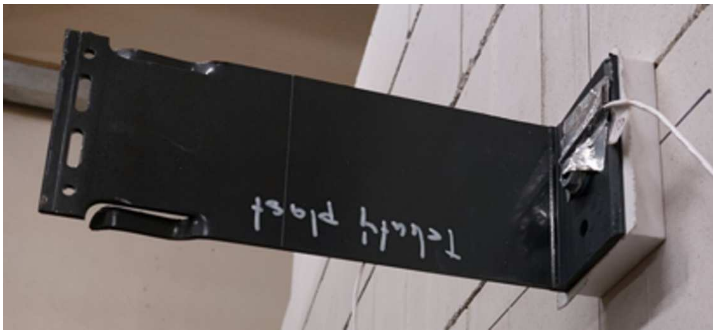

Fig. 2 Wall anchor with a plastic washer put in place on the wall.

Chyba! Nenalezen zdroj odkazů. shows asteel anchor on a 19 mm thick washer on the wall. There is another thermal resistance solution shown in the picture. The anchor is coated with liquid plastic to make the anchor more resistant.

Our research team have made several simulations showing how air is flowing through a ventilated gap. Thermal bridging has been captured on thermal camera during research shown in Fig. 3. Visualization of these simulations is shown in Fig. 4.

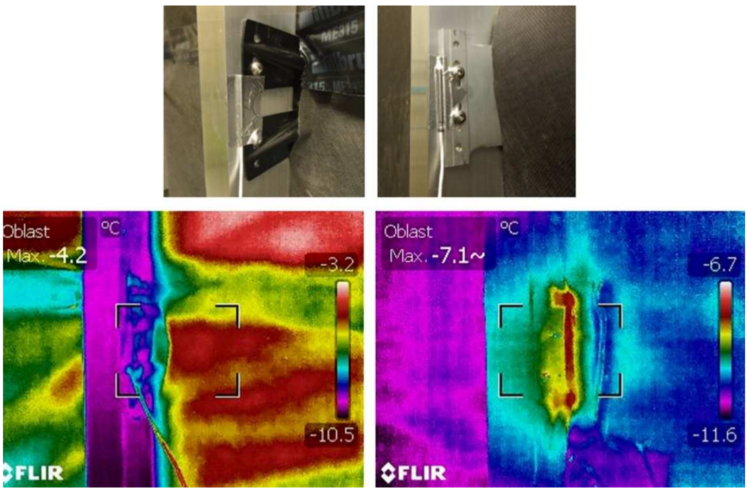

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Fig. 3 Thermal image of an anchor that is hotter than the surrounding surfaces.

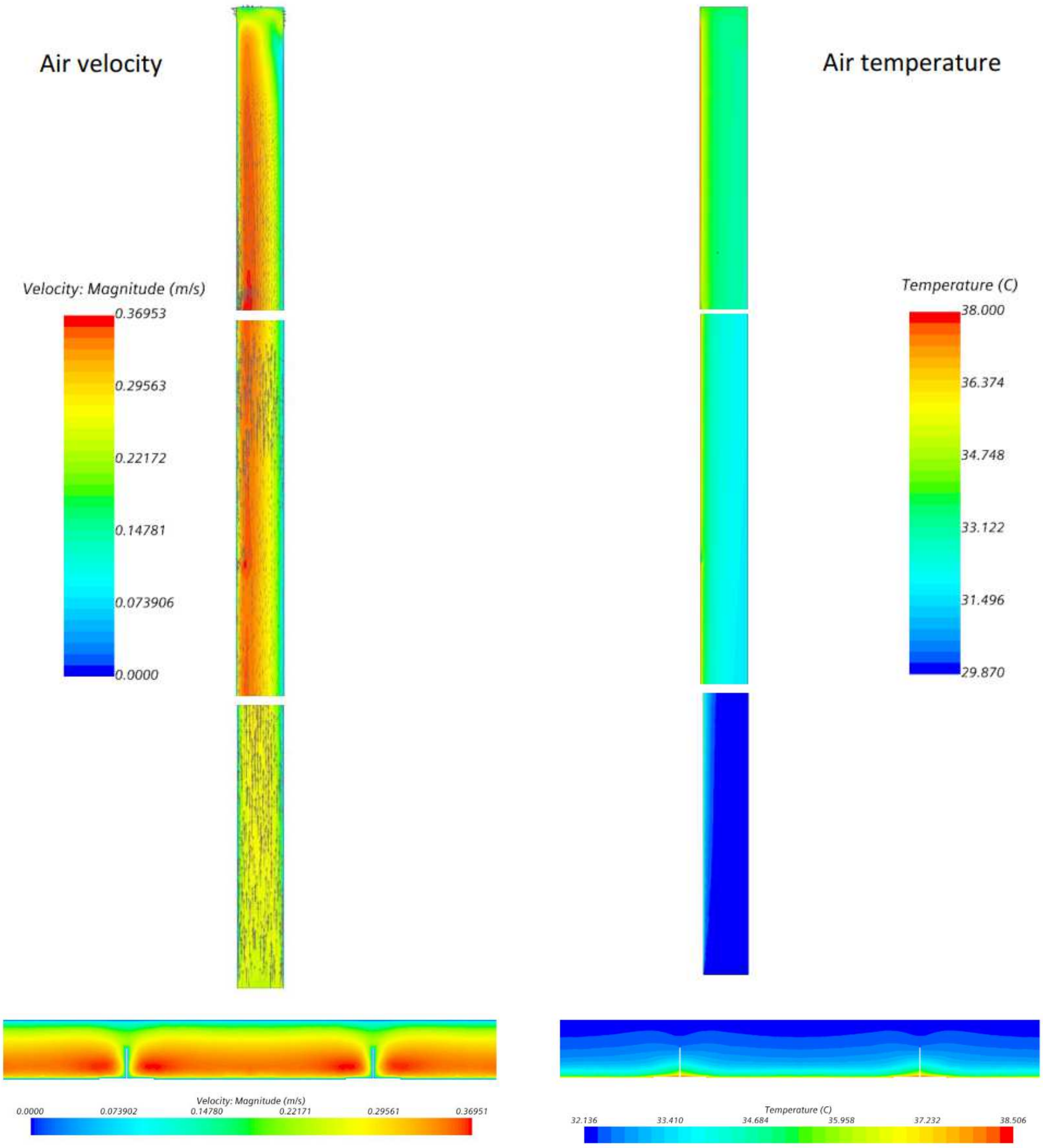

Fig. 4 Visualization of the simulation of air velocity and temperature on ventilated gap height – summer.

In a ventilated facade system, the temperature stratification phenomenon can lead to the accumulation of high temperatures in the upper part of the ventilated gap. This is primarily a result of solar radiation and convective heat transfer. As sunlight strikes the external cladding, it warms the air in the gap between the building envelope and the cladding. Since warm air is lighter, it tends to rise, creating a temperature differential within the ventilated gap. The upper regions of this gap act as a thermal reservoir where heated air gathers, potentially reaching elevated temperatures. It is visible from Fig. 4, which shows a simulation for summer boundary conditions in the Czech Republic, that the temperature inside the ventilated gap can get way above the standard interior temperature (around 20 °C to 25 °C), thus effective ventilation is required for proper thermal balance between the interior and the air gap. Such event was simulated for winter as well. Results of these simulations are shown in Fig. 5.

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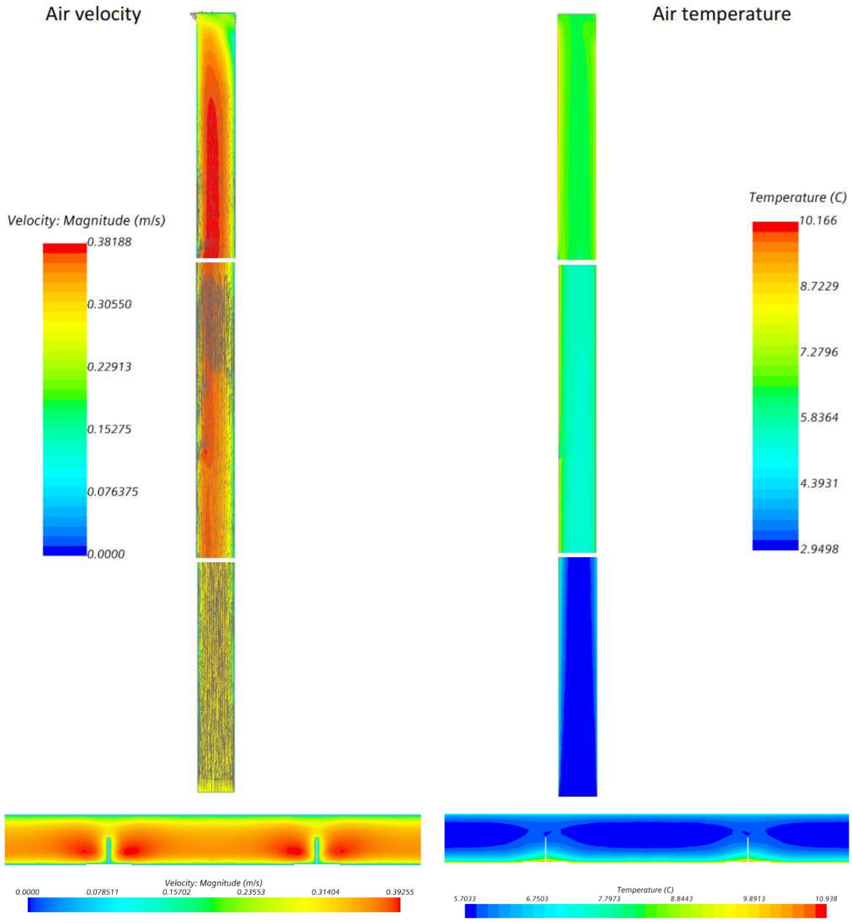

Fig. 5 Visualization of the simulation of air velocity and temperature on ventilated gap height – winter.

There was a simulation using the FSVM calculations that had to show the difference between the heat flow of the ETICS facade system and the conventional ventilated facade. The ETICS primarily insulate the building by reducing heat flow through the wall, while ventilated facades focus on dissipating heat, creating an air gap to mitigate temperature differentials and prevent overheating. The ETICS aim to limit heat loss by insulating the building externally, making the building more energy-efficient, while ventilated facades prioritize thermal comfort by reducing heat buildup and maintaining a stable indoor environment. Knowing this we anticipate that the ETICS could be more efficient in winter and ventilated facade could be more efficient in summer. Fig. 6 shows simulation results.

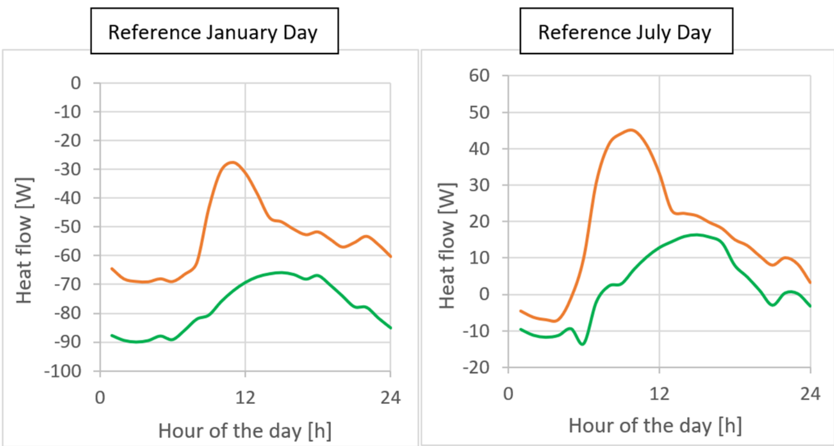

Fig. 6 The heat flow of the ETICS and the ventilated facade during a reference day Orange – the ETICS, green – a ventilated facade.

Fig. 6 shows simulation results. The ETICS shows smaller heat flows during a reference winter day in the Czech Republic. The ventilated facade shows higher absolute heat flow. The negative value means the facade shows heat loss. On the other hand, in the reference summer day in the Czech Republic, the ventilated facade shows lesser heat flow during the day. During the night, early morning and evening hours, the ventilated facade shows heat loss. Note the elevations – they are showing solar irradiation making its effect on facade surfaces.

The smart facade consists of a conventional ventilated facade, shut-off dampers, and a control system. Closing the dampers stops the airflow and creates the air layer that acts as another insulation layer with the thickness of the air gap and thermal properties of an air in the gap. Solar irradiance of outer cladding can create heat gains of the air inside the gap. If the airflow is stopped, the temperature of the air inside the gap and the temperature of the indoor microclimate create a temperature difference which defines the heat flow.

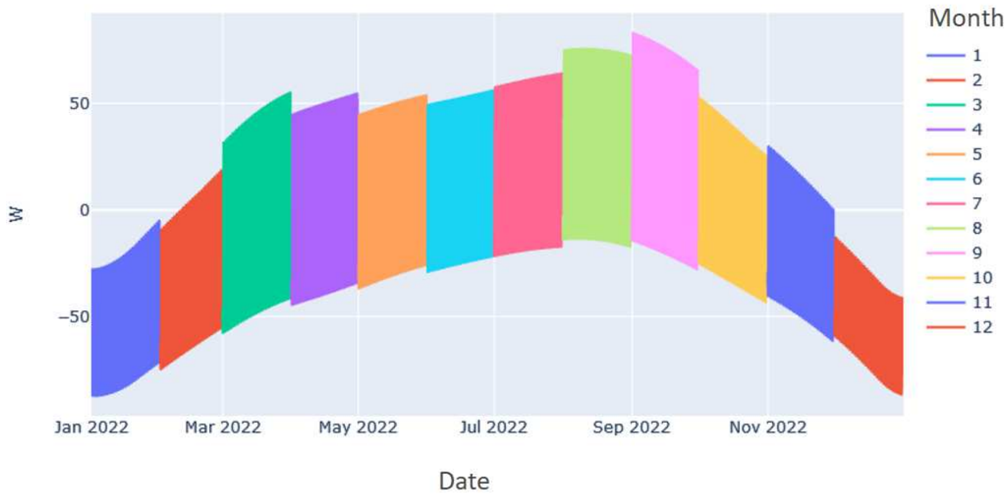

Fig. 7 The FSVM output – hourly heat flow during the year using the ETICS facade system.

FSVM chart shows the simulated heat flow values 24 hours a day 365 days a year. **Chyba! Nenalezen zdroj odkazů.** chart shows the heat flow of the ETICS facade system. **Chyba! Nenalezen zdroj odkazů.** shows the heat flow of a conventional ventilated facade. Note the difference between these two systems. The results are similar to the results shown in Fig. 6. Sudden elevations and lowering determined by month show the presence of the monthly differences between the corrected coefficient values of cladding convection heat transfer coefficients and absorption coefficients.

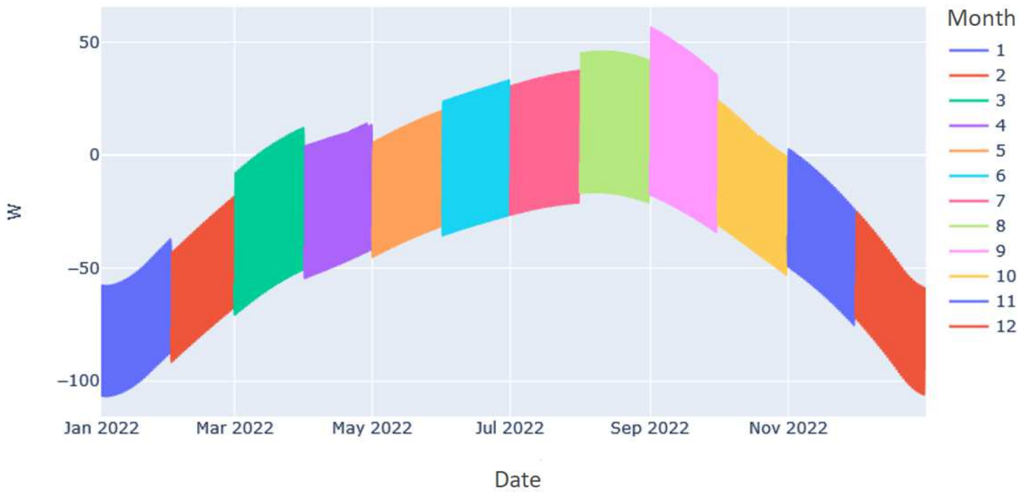

Fig. 8 The FSVM output – hourly heat flow during the year using a ventilated façade.

The chart in **Chyba! Nenalezen zdroj odkazů.** shows how the heat flow changes using a ventilated facade by simply closing the shut-off dampers in winter months. As described previously, the air is supposed to be closed

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inside the gap and create another insulation layer. Note the higher heat flow during March, October, and November. This represents the significance of the solar irradiance. The sun in the Czech Republic in these months has the ideal solar declination angle for the highest irradiance of vertical surfaces. The FSVM has the option to calculate the effect of solar declination and its irradiation for any place on Earth by setting the desired geological latitude and longitude.

The shut-off dampers are constantly closed during January, February, March, October, November, and December. A real smart facade should be able to control the opening and closing of the dampers variably throughout the day and not once per month.

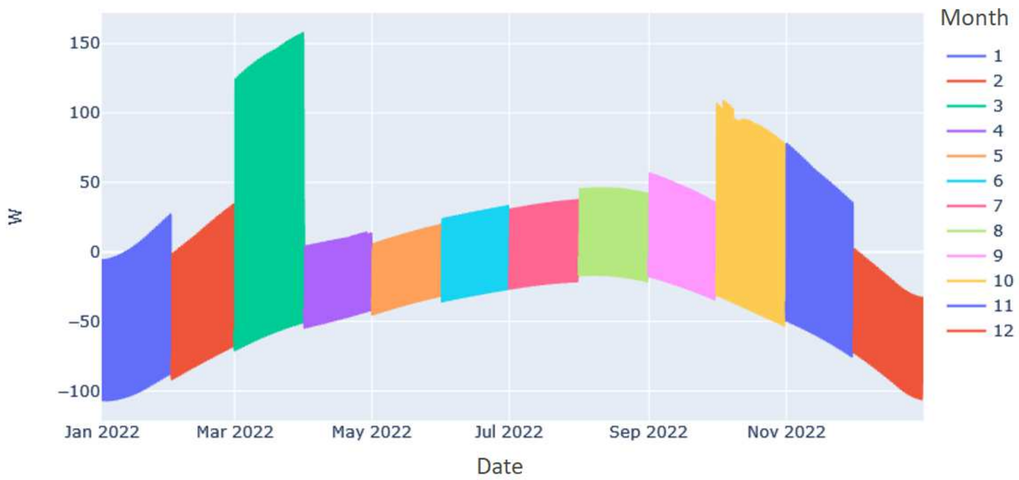

Fig. 9 The FSVM output – hourly heat flow using a smart façade.

Calculated heat flows in numbers are shown in Tab. 3. The heat flow is represented by energy per month for more accurate and more understandable results. These numerical values can be exported from the the FSVM software along with all the hourly simulated values of many other output variables described in Chapter 3 – Data.

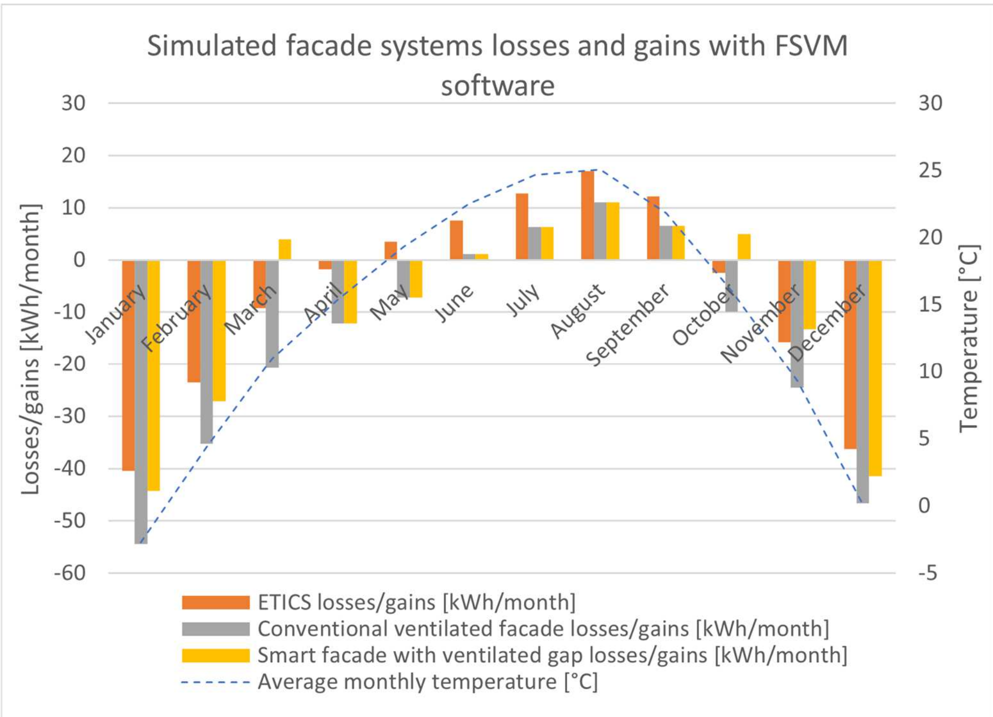

Fig. 10 Comparison of the heat flow of three facade systems and average monthly temperature in the Czech Republic.

Tab. 3 The FSVM output – output heat flows.

Month	Average monthly temperature in °C	ETICS loss/gain in kWh/month	Conventional ventilated facade loss/gain in kWh/month	Smart facade with ventilated gap loss/gain in kWh/month	Comparison of the ETICS vs conventional ventilated facade in %	Comparison of the ETICS vs smart facade in %
January	-2.700	-40.415	-54.430	-44.247	-35	-9
February	4.377	-23.545	-35.262	-27.165	-50	-15
March	10.953	-9.233	-20.769	3.903	-125	142
April	15.357	-1.774	-12.140	-12.140	-584	-584
May	19.321	3.498	-7.167	-7.167	305	305
June	22.511	7.612	1.153	1.153	85	85
July	24.689	12.727	6.283	6.283	51	51
August	25.067	17.032	11.074	11.074	35	35
September	21.837	12.222	6.583	6.583	46	46
October	16.041	-2.486	-9.854	4.946	-296	299
November	9.292	-15.820	-24.564	-13.238	-55	16
December	0.111	-36.256	-46.701	-41.470	-29	-14

5 DISCUSSION

The smart facade research and development has already gone a long way and the research team has a lot of the results so far. Currently, the project is being tested on a prototype ventilated facade along with several additional segments of cladding including green facade or photovoltaic cladding that could be used as a power source for the measurement and control system of the smart facade.

The FSVM software has established itself as a proficient computational resource, derived from our research that delves into fundamental aspects concerning the development of smart facades. This software is under continuous development, particularly in the realm of universality. The aim is to extend its computational applicability to embrace a broad spectrum of conventional ventilated facades, each characterized by a diverse array of parameters.

The primary variables affecting the thermal performance of the facade are the external air temperature and solar radiation intensity. The driving force behind the development of an intelligent facade is unequivocally energy conservation, with the goal of achieving near-zero energy consumption. Leveraging our expertise, we aspire to approach this ambitious as closely as possible.

In accordance with the study's results [9], the research community has been engaged in numerical analyses related to ventilated facades for more than four decades. Concurrent with the broadening capabilities and scope of computing technologies, numerous methodologies have emerged. The authors of this publication have dedicated their efforts to scrutinizing these approaches, conducting experimental validations of various methods, and evaluating their respective benefits, drawbacks, and constraints [9].

The new approach to thermal bridges over the wall anchor caused us to use the more heat-resistant washers between the anchor and the bearing wall. However, there is still lower thermal resistance in the bolts which hold the anchor in the wall. Further research is considering using more heat-resistant bolts and dowels without losing the reliability of the support system. Right now, researchers are testing the load-bearing capacity of the washers and the potential safe usage of glass laminate anchoring bolts which are more heat-resistant.

The shut off-dampers can effectively close the ventilated gap. The effect with closed dampers is effective, especially during the winter season, which should make the smart facade more effective than the ETICS during winter. While having the option to be the most effective solution in the summer so far, the smart facade should be the most optimal. Opening the dampers should make the smart facade act as a conventional ventilated facade thus securing its effectivity during summer. For additional support of this positive effect, the smart facade project considers using a small fan with an electricity supply from photovoltaic panels to enlarge airflow volume in the ventilated gap and ventilate the heated air much more.

Results shown in **Chyba! Nenalezen zdroj odkazů.** and Tab. 3 present simulated heat flows of all three mentioned facade types. There is a significant difference between all three systems and the results are as expected and mentioned in the introduction. The smart facade has a smaller heat flow during summer and the ETICS has a smaller heat flow during winter. The smart facade is still a prototype and it is still in the research phase. New approaches and materials are being applied for the research to create a unique and the most efficient facade system throughout the year.

6 CONCLUSIONS

Drawing from the research outcomes, it is apparent that the development may now be capable of accurately forecasting the structural-physical behaviour both on the surface and within the ventilated facade, in response to variable boundary conditions, with a small margin of error. The results from the software are a keystone to creating optimal output values for a smart facade control system. Understanding how the air flows in the gap, how thermal energy conducts and how convection works inside ventilated facades, leads us to evidence in simulations that smart facades can be a significant energy-saving system of modern buildings and that this project has a sense. A prototype of a smart facade is currently being built at our research centre and it will be provided with additional measurement devices to understand and refine the smart facade system further.

In comparison with the ETICS, the smart facade can reduce the heat flow up to 299% as shown in Tab. 3. With more innovative materials and approaches this number can go even higher and does not necessarily have to be individual for a specific month and boundary conditions. Numbers show a higher efficiency of the smart facade in months where the sun has the most effective declination and is irradiating a vertical plane the most.

As mentioned earlier, the smart facade prototype is going to be tested in different combinations with clear panels, and panels combined with photovoltaic panels and green facade segments. The green facade shows potentially positive properties that can be used along with a smart facade [10].

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