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The Modelling of Panel Radiator Dynamic Behaviour

Modelování dynamického chování deskového otopného tělesa

This paper deals with analysis and modelling of thermal dynamic processes of a panel radiator. The analysis is based on observing the temperature field on the frontal surface of the radiator by a thermal infrared camera. Two different simulation models in Matlab Simulink are presented here. Both are made for the specific panel radiator (a classic type with one panel, 0.5 m height and 1 m long with a single side connection from the top to the bottom). The dynamic behaviour is usually determined by (expensive) measurements, so the main goal is to create such a model that will be simply able to simulate the dynamic behaviour as real as possible for certain similar types of radiators, with minimum input values.

Keywords: *Heating, dynamics of radiators, modelling, Matlab, control of heat power*

Příspěvek se zabývá analýzou a modelováním tepelné dynamiky deskových otopných těles. Úvodní experimentální analýza je založena na sledování teplotních polí na přední teplosměnné ploše otopného tělesa termovizní kamerou. Jsou zde popsány dva rozdílné simulační modely v softwaru Matlab. Oba jsou vytvořeny pro deskové otopné těleso „klasik“ s jednou deskou (typ 10) o rozměrech 500 × 1000 mm (výška × délka) a s připojením k otopné soustavě jednostranně shora dolů. Dynamika je v současnosti spolehlivě zjišťována téměř výhradně nákladným (termovizním) měřením, a proto je základním cílem vytvoření takového modelu, který by byl jednoduše schopen generovat údaje o tepelné dynamice otopných těles co nejvěrněji a s dosazením minimálního počtu vstupních dat.

Klíčová slova: *Vytápění, Dynamika otopných těles, Matematické modelování, Matlab, Regulace tepelného výkonu*

INTRODUCTION

All the individual radiators are important accumulation elements in heating systems and, therefore, they could be imagined as resistors. The dynamics of the radiators can be described with their thermal inertia. The thermal dynamics (and inertia) were measured with an infrared camera (Flir ThermaCam type T460). The selected radiator was monitored under simplified laboratory conditions in a so-called open space (according to DIN 4704).

There are two modelling approaches described here, the processes of both are quite different. The first model is based on physical laws, where the heat output is determined only on the water side by the calorimetric equation. Then the heat output is shared through the wall of the radiator into the ambient air. The second model is the first order stochastic discrete black-box model. It identifies the dynamic parameters only on the basis of the real measured data without any prior information about the physical dependencies. The result of this approach is a discrete dynamic model, which is described by a differential equation.

Compared to the previously presented results [1], [2], there is a fundamental difference. The discrete black-box model is able to generate a complete dynamic picture for the transferred heat to the room at different temperature levels both within the heat-up and cool-down stages. The entire model is based on the unique record made by the thermal camera. The static properties for the different mass flow rates and temperature parameters for this model also were measured. Such dynamic models help to increase the efficiency of the control processes and controller designs for specific applications and different boundary conditions.

PHYSICAL MODEL

Experiment

A basic type of a panel radiator was selected for measuring: a single panel (type 10) with dimensions of 500 × 1000 mm. The radiator was connected in a nominal way – a single side from the top to the bottom. The nominal values of the temperature and mass flow rate were determined and set at the beginning. The thermal camera took an image once every five seconds – thus, a series of thermography images arose. The dependence of the radiator´s surface temperature against the time was obtained. The mean surface temperature of the radiator t_p and its dependence against time may be then evaluated within the area of the frontal projection surface of the radiator. We can say, that the surface temperature is equal to the temperature of the water – this simplification allows the fact that the heat transfer on the side of the water is more intense than the heat transfer on the side of the air. The thermal conductivity coefficient of the radiator´s body material is high and the thickness of the radiator´s wall is relatively small, at the same time. Therefore, the water temperature drop caused by the heat transfer on the water side and the heat conduction in the material can be neglected. The mean temperature of the water t_{wm} is then approximately equal to the mean surface temperature of the radiator t_p on the air side.

The dynamic processes were captured from the initial changes of the mean surface temperature (i.e., without any dead time) until the new steady state. Then, using the procedure described in [3], the characteristic curves can be converted from the dependence of the mean surface temperature against the time to the dependence of the relative heat output against the time. The resulting transient curves from the experiments, used to create the model, were presented, e.g., in [4].

Procedure

The methodology of the approximation of the measured processes was based on the procedure known as the approximation by Strejc ([5], [6]). It can be only used if the system response is not oscillating. The real function is approximated by a second order proportional system with two different time constants (when $\tau_u < 0.104$) or by an n-th order system with two equal time constants (if $\tau_u > 0.104$). The choice of the system depends on the value of the parameter τ_u. This parameter is typically less

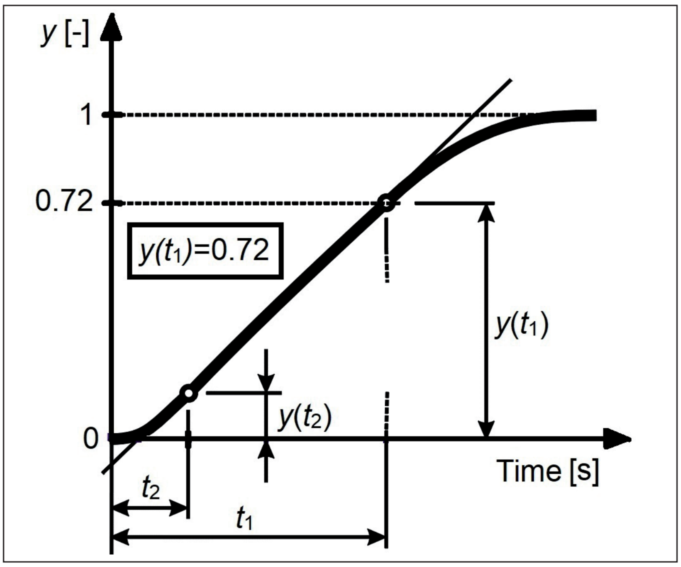

Fig. 1. The principle of determination of the time constants according to Strejc´s method

than 0.104 in the field of the radiator's use and, therefore, only the case of the 2nd order approximation will be described.

$$\tau_u = \frac{T_u}{T_n} \tag{1}$$

Where τ_u is the dimensionless parameter for the approximation selection; T_u is the process delay [s]; T_n is the process reaction rate [s]. If $\tau_u < 0.104$, then the final shape of the transmission function is according to Equation (2), where $\tau_{0,1}$ and $\tau_{0,2}$ are the individual time constants.

$$G_{(s)} = \frac{K}{\left(\tau_{0,1}s+1\right)\cdot\left(\tau_{0,2}s+1\right)} \tag{2}$$

The gain *K* is given by the ratio of the newly stabilised value of the output variable Δy to the steady value of the input variable Δx. The approximation theory is based on Equation (3).

$$y(t_1) = 0.72 \cdot y_{(\infty)} \tag{3}$$

Time t_1 is subtracted from the respective transition curve for the value 0.72.*y* and the sum of the time constants $\tau_{0,1}$ and $\tau_{0,2}$ is calculated according to Equation (4):

$$\tau_{0,1} + \tau_{0,2} = \frac{t_1}{1.2564} \tag{4}$$

After that, it is necessary determine time t_2 according to Equation (5) and the value of $y(t_2)$ is subtracted from the corresponding transient characteristic. An example is shown in Figure 1.

$$t_2 = 0.3574 \cdot \left(\tau_{0,1} + \tau_{0,2}\right) \tag{5}$$

Depending on the tabulated values (e.g., [5]), the ratio of the time constants τ_2 is determined. The constants $\tau_{0,1}$ and $\tau_{0,2}$ are then simply calculated from $\tau_2 = \tau_{0,2}/\tau_{0,1}$. It is easy to set time t_2 from Equations (4) and (5) at the same time.

Model progress

The change in the inlet water temperature flowing into the radiator was considered as the input to the model (as a step change). At the beginning, the radiator is temperature-balanced with its environment and then water of a nominal temperature (according to EN 442, it is 75 ° C) is introduced into it. The output of the model is the desired dependence of the mean surface temperature of the radiator against time, which can be converted into the dependence of the heat output against time by the procedure given in [3].

The entire approximation process is included in the model, and the determined values of the gain and time constants are then inserted into the transmission function. At the beginning of the development process,

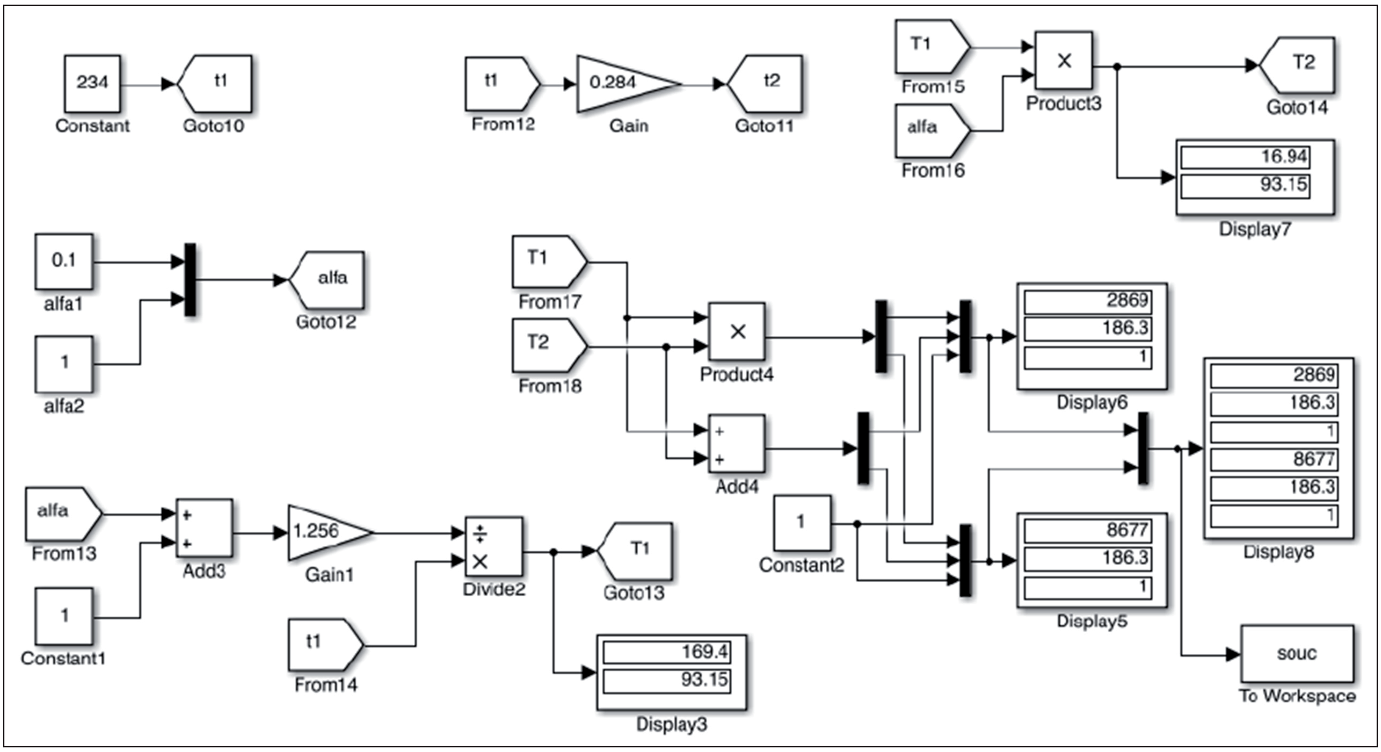

Fig. 2. The scheme of the approximation model for the 2nd order function

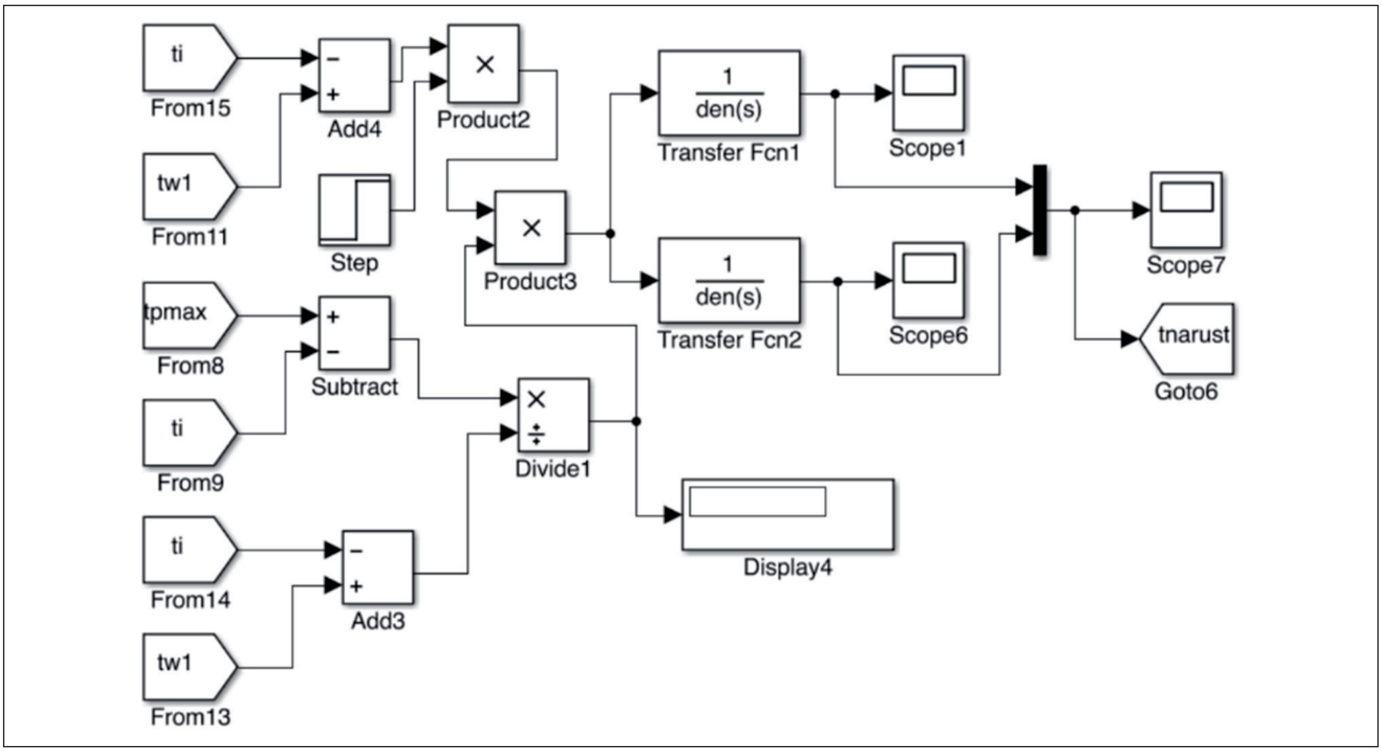

Fig. 3. The scheme of the model with the transmission functions

it was necessary to divide the model into two independent programmes that had to be run in the right order. The first of these is the programme for determining the function approximation (see Figure 2). Then, the simulation programme for mean surface temperature started, based on the approximated outputs (see Figure 3). A two-channel approach to the approximation calculation (it is allowed by Strejc´s method) has been introduced. In the first channel it is considered with the two time constants as mentioned above (because $\tau_u = 0.1$ and it is referred to block "alpha" in the model in Figure 2). The second channel of the calculation then considers that $\tau_u = 1$. This simplifying assumption leads to the calculation of the transmission functions with only one time constant. Such a solution leads to a more flexible approximation based on the input data and it is not necessary to work with one fixed transmission function only, but with the so-called flexible transmission.

It was a natural development to join up two consecutive programmes into one set, which would be able to connect the input values of the necessary variables and coefficients. This was achieved by replacing the blocks of the transmission functions with the integrator blocks. The integrator was introduced as a transmission block with a value of $G_{(s)} = 1/s$. The appropriate combination of these blocks and the constants can provide the same functions as the transmission ones.

Using the flexible transmission model for the heating-up of the radiators, the final model of entire dynamic process of the radiator was built. It was also necessary to build a cool-down phase model for this simulation. However, this is a simpler process than the heat-up in the mathematical description. Since the process delay is almost undetectable, the resulting transition curve may advantageously be referred to as a first order system. A significant source of the cool-down model uncertainty is the estimate of the heat transfer coefficients both on the water and air sides. Another disadvantage is also the need to insert a dynamic parameter for each radiator which represents the value of the mean surface temperature in time that corresponds to a 72% change between the original and the new steady state. This fact makes this model very difficult to use in practice because this value is generally unknown.

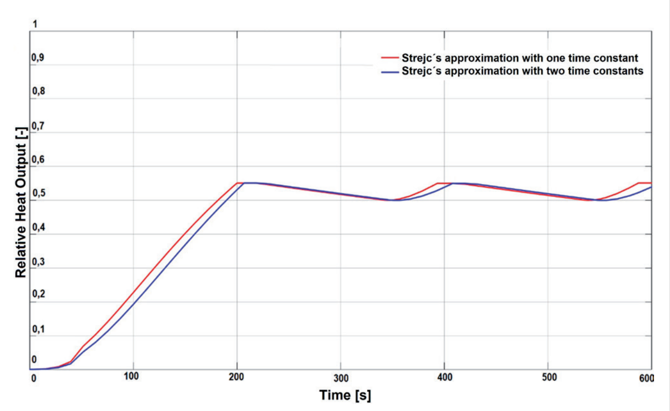

Fig. 4. The dynamic behaviour of the radiator – model. A heat output demand of 62.6 %; A range of proportionality of ± 1 K

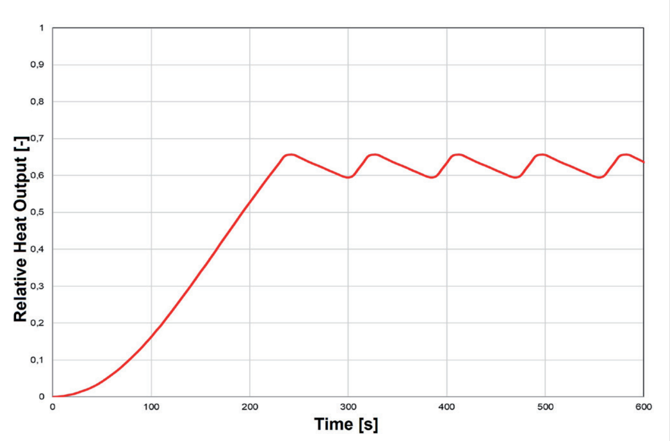

Fig. 5. The dynamic behaviour of the radiator – experiment. A heat output demand of 62.6 %; A range of proportionality of ± 1 K

It was necessary to link the processes of heating-up and cooling-down by a function, which is able to switch between them. We can use the "Relay" block in the Simulink environment. It disposes a two-position signal switching with hysteresis. In fact, this block can be imagined as a P-controller (i.e., a thermostatic liquid head).

Real systems always have some dead time which is introduced by the "Transport Delay" block. It has to be entered individually for each radiator within this model and, therefore, this is unfortunately impractical. After creation of the decision signal model, the complex dynamic behaviour of the radiator can be generated. An additional condition is that the temperature at the end of the individual phases is always used as the initial condition for the next phase. Finally, it was necessary to add a block of calculations for determining and setting the required range of proportionality within which the resulting control curves will move. This also gives the possibility to set the real range of proportionality of the actual P-controller that will be used. For lucidity, individual calculation blocks and other auxiliary calculation mechanisms (not illustrated in the figures above) were built into several subsystems that form a compact final model. The result is the mean surface temperature of the radiator and its heat output.

Results

Only small part of the graphical results from the experiments and the Matlab models are presented here. It is possible to simulate any heat output demand of the radiator within its power spectrum and any range of proportionality of the P-controller. The two curves (in Figure 4) are given by the two calculation channels with the different approach to the time constants. The dynamic behaviour compiled from the real measured data is shown in Figure 5. The conclusion of this physical model is listed below in the appropriate section.

DISCRETE BLACK-BOX MODEL

Experiment

The experimental measurements were not performed primarily for the purpose of determining the absolute values of the heat output, as usual, but, above all, for comparing the radiator's dynamic response and its behaviour in the different phases of the temperature spectrum.

Figure 6 presents a scheme of the measuring track with two independent heat sources. This arrangement is necessary to provide a (quasi) step change of the inlet water temperature. In addition, one of the sources is connected to the accumulation storage tank for increasing the temperature stability. There are also additional electrical heating cartridges in the storage tank. First of all, the mass flow rate was set, which corresponds to the nominal conditions specified by the radiators manufacturer. Both heat sources were connected to the by-pass at this moment. All the temperature changes were then performed at this constant mass flow. The dynamic response of the radiator on the mass flow rate changing was measured in a different measuring track configuration (with only one heat source). At the point, where the supply pipes from both sources meet, the desired temperature step change is ensured by means of a manually operated ball valve. The mass flow rates were measured by ultrasonic flow meters. The flow corrections were made according to the main flow meter, shared for both heat sources. Furthermore, the water temperatures at the inlet and outlet of the radiator were monitored.

So, the simple heating-up process between two steady states only was not observed (as for the physical model), but three stabilised temperature levels during the heat-up were provided. The inlet water temperature was changed to 50, then 60 and finally to 75 °C, at a constant mass flow rate.

It is not common in practise to change the inlet water temperature to the radiator in steps, but under laboratory conditions, it is a possible way to ensure the parameter that we are able to mathematically describe and evaluate. Then it is possible to observe and identify the dynamics of the radiators in the different phases of the temperature spectrum, and, what is the most important, it is possible to made models of their behaviour where the dead time is a necessary parameter representing the above-mentioned thermal inertia.

Figure 7 presents an evaluated record of the behaviour of a panel radiator from the experiment. It includes not only the mean surface temper-

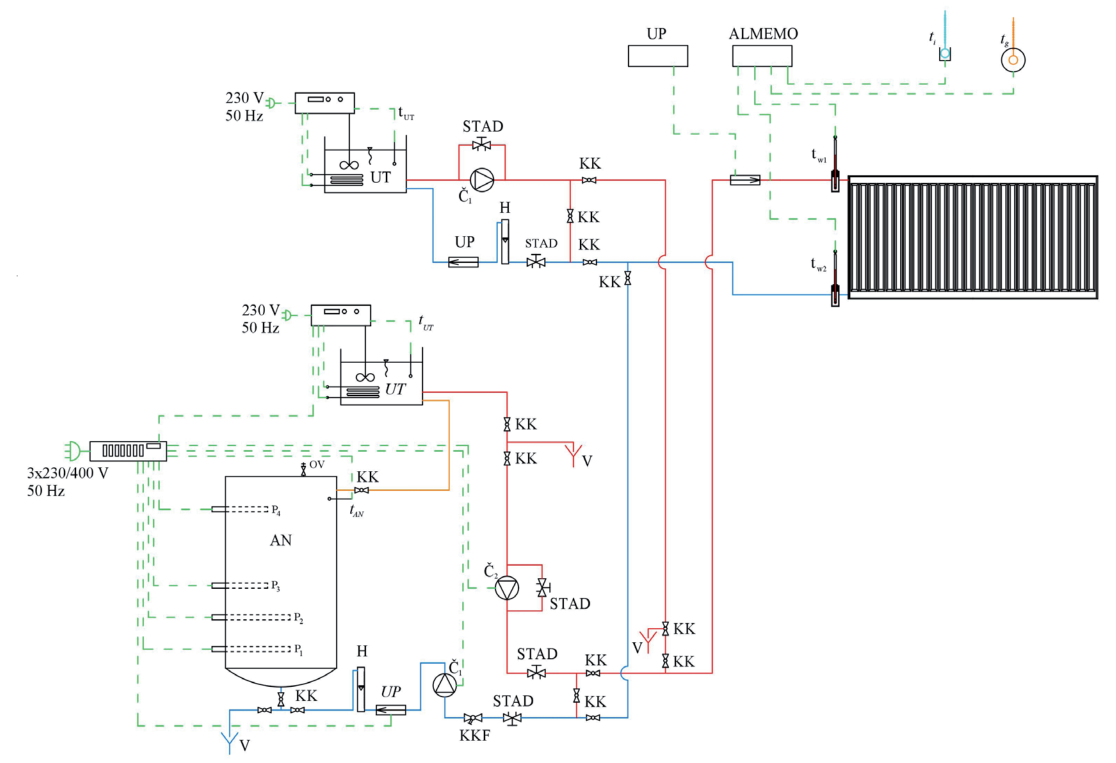

Fig. 6. The scheme of the experimental measuring track for the radiator with two independent heat sources

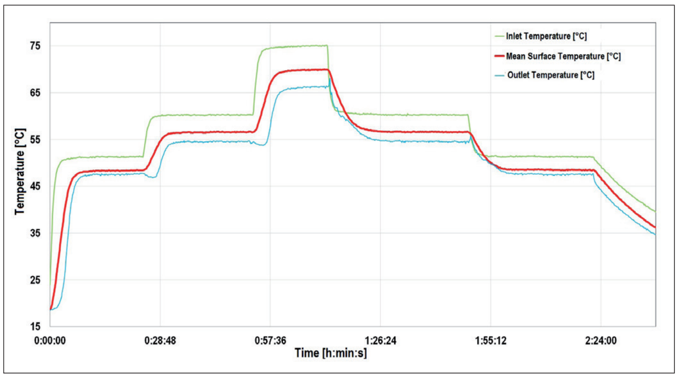

Fig. 7. The record of the operational dynamic behaviour of the radiator 10 – 500 × 1000 as a background for the model

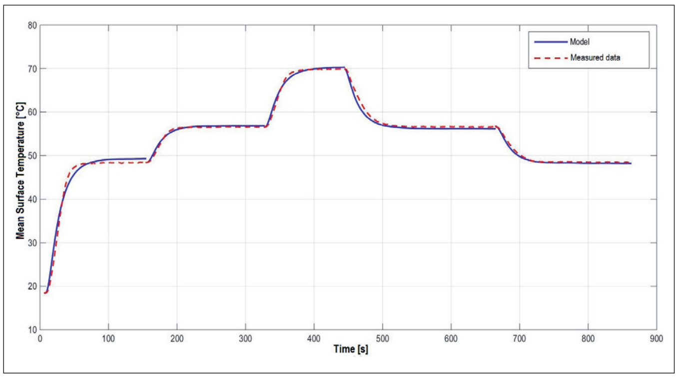

Fig. 8. The validation of the black-box discrete stochastic ARX model for the dynamic behaviour of the radiator

ature, but also the inlet and outlet water temperatures. It is clear that the changes in the inlet water temperature are almost steps. Unlike the outlet temperature, where due to inappropriately manipulation with the valve, we can observe a short-term negligible decrease. This drop at one point in the measurement does not have an effect on the mean surface temperature of the radiator.

Model progress

The basic idea is that the continuous system or its dynamic effects are approximated by a discrete model with a general transmission *G*(z) with a suitable selected sampling time period. After careful analysis of the mathematical identification options, an ARX model approach (**A**uto**R**egressive with an e**X**ogenous variable) was chosen. AR models are generally able to describe random auto regression processes of any order. The discrete output values always depend on the actual input value and on the past output values that are weighted by the appropriate coefficients - hence the name of the model - autoregressive. The entire process of the mathematical identification using the ARX model is beyond the scope of this contribution and can be found in, e.g., [7]. If the transmission function is set as $G_F(z\text{-}1) = 1$, then the final derived equation of the discrete dynamic system for the model can be written in the following differential form:

$$t_p \cdot (\tau + 1) = a \cdot t_p(\tau) + b \cdot t_{w1}(\tau) \qquad (6)$$

Where t_p is the mean surface temperature of the radiator against time τ [°C]; τ is the time [s]; *a* and *b* are the dimensionless coefficients of the differential equation; t_{w1} is the inlet water temperature [°C]. A sampling time period of 10 s was chosen.

Only the first-order polynomial was used for the simplest possible expression of the so-called Z-transformation and the subsequent script in Matlab. At the same time, the results of this model simulated the real measured dynamics of the radiator with satisfactory accuracy, see the following section.

It can be stated that the ARX identification method is based on the smallest square method. Basically, the point is to minimise the sum of the quadratic deviations of the estimated parameter vector (the real set of the mean surface temperature values $t_p(\tau)$) from the real measured values. A complete description of the so-called predictors – special vectors intended for the parameter estimation is described in [8].

Results

Figure 8 shows the comparison of the results obtained by the mathematical model and the real measured course. The maximum deviation from the measured values is up to 2 K of the mean surface temperature. As stated above - the model uses the simplest approach – a first-order function. In order to provide better accuracy of the mathematical model, it is possible to use an approximation of the second (or higher) order, where the deviation would be reduced below 1 K. However, those models require a much more complicated mathematical expression and a more complex controller design for their analytical solution.

Since a deviation up to 2 K is sufficient for the purposes of designing controllers of the radiator's heat output, the further specification of the mathematical model by a higher order approximation is no longer necessary.

CONCLUSION

Physical model

The physical model is only limited to a specific panel radiator type 10 – 1000 × 500 and to specific ambient conditions. To extend the usage of this model, it is necessary to further investigate the behaviour of other types of radiators under other conditions. It means further experiments. The approximation was carried out according to the method by Strejc. This means that it is necessary to enter the time when the 72% change in the transition function occurs. However, this value is not normally supplied by radiator manufacturers.

The displayed output from the model in Figure 4 shows a greater thermal inertia and lower relative heat outputs at the same time. The reasons for these deviations lie in the fact that a constant ambient temperature is introduced for the model. In this case, it was necessary to choose the mean surface temperature as the controlled variable. The range of proportionality, thus, relates to this value and not to the ambient air temperature. To solve it, it is necessary to construct a model of the entire space in which the radiator is located. Thus, it will be possible to simulate heat flows in such a space and to influence the varying ambient air temperature. The ambient air temperature then could be used as the feedback through the connected model of the P-controller. This will be the subject of the further development of this model.

Discrete black-box model

An interesting fact is the effect of the difference between the inlet water temperature and the mean water temperature in the radiator on its thermal inertia. It has been confirmed that at the higher value of this difference, the faster the processes take place. This fact is confirmed by the trend in all parts of the spectrum. This could be described by the time constant, which is the highest for the temperature change from 50 to 60 °C (3 min) and the lowest (2 min 45 s) for changing the temperature from the ambient temperature to 75 °C (not illustrated in Figure 8). Although the differences in the time constants are very small and sensitive to a proper evaluation, it is necessary to take this fact into account for the dynamic behaviour models. Of course, the specific thermal capacity of the radiator has a significant effect.

The rate of the thermal change also depends on the mass flow rate of the water. In order to construct the model, it was also necessary to map the behaviour of the radiator for the different flows. Thus, so-called static characteristics arise. The very practical knowledge was confirmed – the quality control, i.e., the change in the inlet water temperature is more effective than the regulation quantitative (varying mass flow). While the control of the heat source and the heating system is mostly qualitative, the local control of the heat output of the radiator is ensured by a quantitative change (P-controller) and, consequently, by a different water temperature drop inside the radiator.

It is evident that controlling the mass flow is not very effective for increasing the mean surface temperature, i.e., the heat output of the radiator. Manufacturers of thermostatic control valves can only partially compensate this effect by different valve characteristics. Generally, we should choose such parameters that ensure that a certain change of mass flow causes the same change in the heat output. The goal is linearity. Therefore, it is necessary to focus on the influence of the inlet water temperature. From the measured data, it is obvious that (for any mass flow) any increase in the inlet water temperature causes an almost linear increase in the heat output. From this point of view, it can be stated that the lowest inlet water temperature to the radiator is preferred, because the higher the inlet water temperature approaches the indoor air temperature, the more the dependence between the mass flow and the heat output is linear. Based on the above-mentioned analysis (in terms of the effective operation of the radiators and the circulation pumps), it is recommended to provide an inlet water temperature in the range from 50 to 65 °C and a temperature gradient in the radiators from 15 to 20 K. This is why it is very preferable to use condensing technologies, renewable heat sources or heat pumps. It is erroneous to assume that low-temperature heating systems only include a floor or wall heating. Heating systems with radiators, for today’s building, envelope properties and can be designed as low-temperature systems without any problems with, e.g., the size of the radiators.

The black-box model can be applied to other radiators, but they have to be made with the same material (steel), with the same number of panels and with a length/height ratio of a radiator of no more than 3. For other radiators, the model needs to be verified by further experiments. This model can help with finding the appropriate value for the settings of the controllers suitable for the specific type of radiator.

In the long-term research, there are effort to create a universal model that provides an overview about the dynamics of different types of heating surfaces. However, because of their great diversity, it is clear that such a model is very difficult to make. The aim of this article is to make the readers acquainted with the possibilities of modelling a radiator´s behaviour.

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References

[1] BOHÁČ J., BAŠTA J. Dynamické chování otopných těles s ohledem na regulační zásah. In: *Proceedings of Conference Heating Třeboň 2013.* Prague: Společnost pro techniku prostředí, pp 120-124.

[2] BAŠTA J., ŠIMEK J., VAVŘIČKA R. Dynamické chování deskových otopných těles. *J. of Heating, Ventilation and Sanitary Installation.* 2008,17, pp 129-134.

[3] BOHÁČ J. *Diploma thesis.* Dynamické chování otopných těles. Prague: CTU in Prague, 2012, p. 136

[4] BOHÁČ J. *Thermography Data of Panel Radiator Dynamic Behaviour for Simulation Model.* Central Europe towards Sustainable Building 2016 - Innovations for Sustainable Future. Prague: Grada Publishing, 2016, pp 1014-1021.

[5] STREJC V. O možnostech vyššího využití teorie regulace v praxi. Prague, 1958.

[6] KUBÍK S., KOTEK Z., STREJC V., ŠTECHA J. *Teorie automatického řízení I.* Prague/Bratislava: SNTL/Alfa, 1982.

[7] HAVLENA V., ŠTECHA J. *Moderní teorie řízení.* Prague: CTU in Prague Press, 1994.

[8] MODRLÁK O. Modelování a diskrétní identifikace. *Studijní materiály.* Liberec: TU Liberec, 2004,

[9] BREMBILLA C., SOLEIMANI-MOHSENI M., OLOFSSON T. Transient model of panel radiator. in: *Proceedings of 14th Conference of IBPSA.* Hyderabad, India, 2015, pp 2749-2756.

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Importance of Distance Ring in Panel Radiators

Důležitost distančního kroužku u deskových otopných těles

The paper deals with the summary and comparison of surface temperature results from mathematical simulations for different turning and geometry of distance rings based on numerical values of the temperature field on the panel radiator front plate. The changes in flow through individual channels are also compared with respect to the distance rings and the influence of velocity field on temperature field is commented. The results of the temperature and velocity fields for the two-way connection of the radiator for the given cases are given below.

Keywords: *CFD; heating radiator; distance ring*

Příspěvek se zabývá shrnutím a porovnáním výsledků povrchových teplot z matematických simulací pro různá natočení a změnu geometrie distančních kroužků na základě numerických hodnot teplotního pole na přední desce otopného tělesa. Jsou také porovnány změny v proudění jednotlivými kanálky s ohledem na změnu distančních kroužků a je komentován vliv rychlostního pole na pole teplotní. Dále jsou uvedeny výsledky teplotního a rychlostního pole pro oboustranné napojení otopného tělesa pro uvedené případy.

Klíčová slova: *CFD; otopné těleso; distanční kroužek*

INTRODUCTION

The panel radiators are produced by pressure welding of two steel plates. In the corners, a distance ring is inserted between the plates into the distribution chambers to maintain the required distance between the plates. Steel plates are pressed using press heads that are unified for the entire production line of the manufacturer. Thus, only the dimensions of the radiator plate change, but the shape of the channels and distribution chambers remains the same [1]. It is not appropriate to change the shape of the upper distribution chamber e.g. by constant static pressure because the customer requires aesthetically panel radiator parallel to the parapet. It would also have to be a different press head for each length of the radiator, which is not cost-effective.

The objective of this research is the uniformity of the temperature field on the front panel of the radiator. This equalization of the length of the radiator has an effect on heat transfer to the space, in particular to compensate for cold convective flow which arise in the windows below which the radiator primary placement. Another aspect is psychological, where it is better perceived when the radiator is warm to the touch along its entire length. The approach to the solution of temperature uniformity is not through the change of the geometry of the distribution chambers or whole radiator, but through the distance ring, which is a required part of the radiators from the technological and construction point of view.

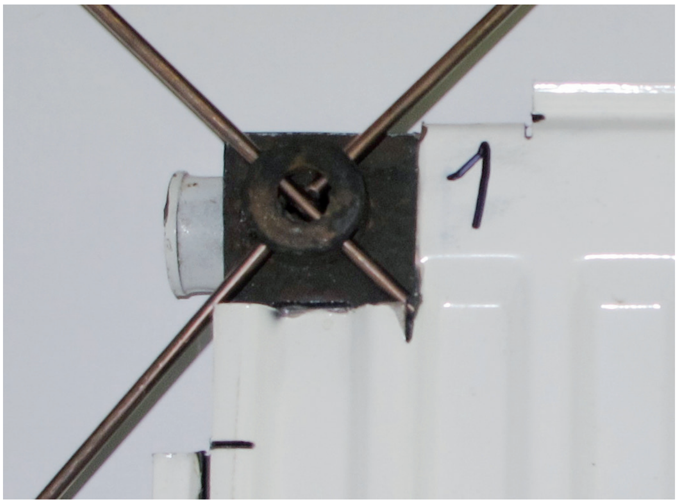

Fig. 1 Old type of distance ring with multiple holes and random turning

Previously, distance rings were made with multiple holes and their turning in the upper distribution chamber was completely random and therefore had different leaks into each radiator. It can be seen in Figure 1 Today produces distance rings with one hole directed in the axis of the upper distribution chamber. The distance ring by its change of turning around its axis and hole geometry affects the flow in the entire radiator.

MATHEMATICAL SIMULATION

Distance ring geometry and first results from mathematical simulation were presented in paper [2]. The temperature field was compared with the experiment and there was a visible similarity within the distribution of the temperature field captured by the thermal imaging camera. Thermal IR imaging has proved to be a powerful technique for studying the thermal behaviour of panel radiators [5]. Description of the velocity field near the inlet of the distance ring showing the bifurcation of the primary flow to the upper and lower edges of the distribution chamber, which mainly affect the flow in the second channel. It was therefore appropriate to focus on the modification of the simulation model, in particular the more detailed meshing of the boundary layer within the radiator and the selection of another turbulence model.

A description of the creation of a new mathematical model including the setting of a mathematical simulation and assessment of a suitable turbulence model is given in [3]. This mathematical model was much more accurate and with better modeling of the boundary flow layer at the walls. The results of the velocity field near the inlet of the distance ring confirmed the same character and the primary flow from the hole of the distance ring remain uniform as shown in Figure 2.

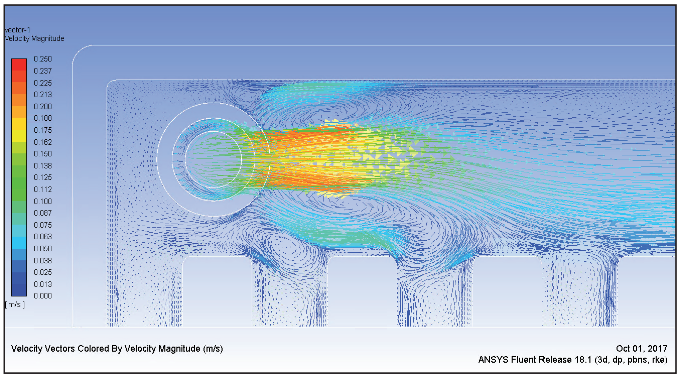

Fig. 2 Vector field of velocity profile in the area of the input distance ring [3]

The comparison of surface temperatures was evaluated based on the displayed temperature fields. This can, of course, be perceived subjectively, and so in this article a comparison of the surface temperature values on the area of the front plate divided by length or height into sections is given. The body was divided into ten sections by length and height, and the mean temperature was evaluated in each. The ideal situation would be equal to the average temperature of each section along the length of the radiator.

COMPARISON OF TEMPERATURE FIELDS

At first, the effect of the turning the distance ring was observed [3]. The assumption was that by turning the distance ring towards the upper distribution chamber, the flow to the right half of the radiator will increase and thus the mean temperature in this part will increase. The distance ring was turned by 10 ° and 20 ° from the axis of the upper distribution chamber towards its upper edge. The turning is seen in Figure 3. As a result of the turning, the flow rate in the second to fourth ducts was reduced and a cooler area was formed in the lower section. The flow to the right side of the body was also increased as expected, but there was no significant increase in mean surface temperature or uniformity along the body length. This is also evident in Figure 5 and Figure 6. The results for the turned distance rings show the lowest mean temperatures in the first section in which the first three channels are just included.

As the results of the mathematical simulation show, the turning of the distance ring towards the upper edge of the distribution chamber does not have a positive effect on the uniformity of the temperature field of the body. If the distance ring is turned clockwise through its hole, the flow in the first ducts will increase significantly. Thus, another direction of research has been given with a view to changing the geometry of the distance ring, ie mainly its holes.

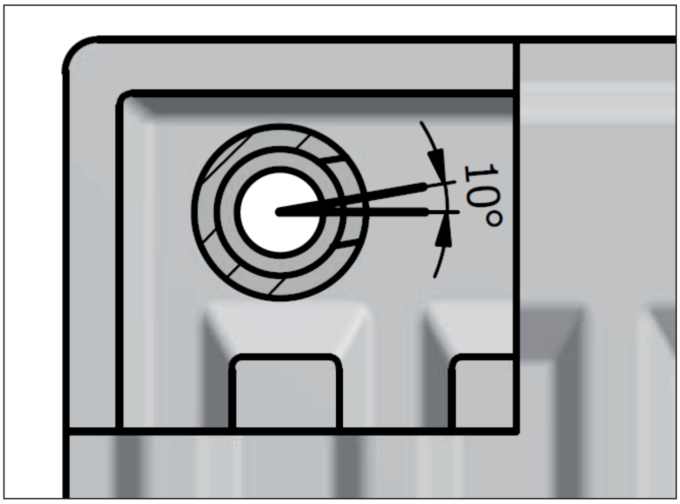

Fig. 3 Turning of distance ring from the axis of the upper distribution chamber towards its upper edge by 10°

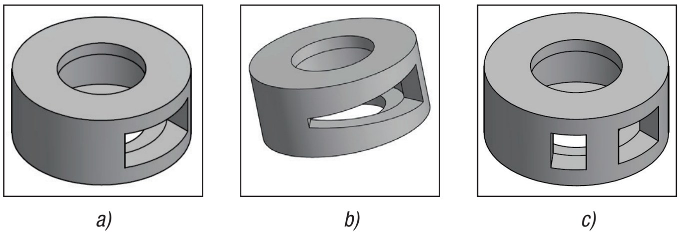
a) *b)* *c)*

Fig. 4 From left – a) distance ring with one hole; b) wedge hole; c) two holes 10/3

Furthermore, a distance ring with a wedge-shaped hole was formed [4]. Its model is shown in the middle in Figure 4. The result is, according to Figure 5, that the temperature field in the first sections has a higher mean temperature, but which decreases along the length of the radiator. It would be preferable to influence the flow so that in the first four segments decreased mean temperature.

Changing the size or shape of one hole in the distance ring does not uniformize the temperature field, because it is mainly about correctly adjusting the direction and speed of the flow from the distance ring. It is appropriate to maintain the portion of the flow in the direction of the upper distribution chamber and then point the second hole towards the channels that showed lower flow, and in its lower part was thus achieving lower surface temperature. The same assumption was made for the wedge hole, but by dividing it into two holes, the flow can be better directed.

We have therefore focused on a distance ring with two holes. The area of the two holes will be as large as the area of one hole. Split ratio 10/3 is selected, where the larger hole will aim at an angle of 20 ° to the upper edge of the distribution chamber, and a smaller hole will be directed between the second and the third channel at an angle of 30 °. According to the results of the mathematical simulation, the average temperature in the first sections decreased compared to the turned rings or the wedge hole. The temperature field shown in [3] shows the decrease of the cold part in the lower part of the second to the fourth channel. The assumption was therefore partially met.

However, there is no change in the temperature field in the second half. To achieve this change, it is necessary to increase the flow velocity in the

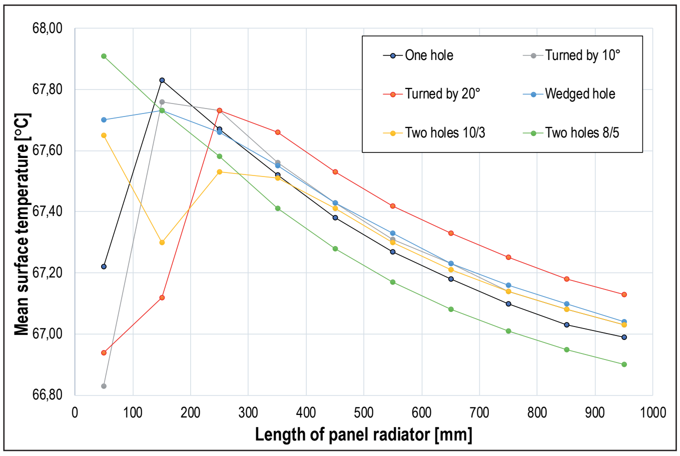

Fig. 5 Comparison of mean surface temperatures for individual sections along the radiator length

upper distribution chamber to cool the water less. In another mathematical simulation, the split ratio of both holes is changed from 10/3 to 8/5 with the assumption that the flow velocity in the upper hole is increased and thus the temperature field in the second half of the body is affected. However, the temperature and velocity fields did not evolve with respect to requirements. Visible change is again in the first half of the radiator, where there was an increase in flow rate in the upper part of the first channels, thus causing the channels to heat up more deeply and the temperature field appears more uneven than in the previous simulation.

It was a comparison of surface temperatures along the length of the radiator. It is also possible to compare the mean surface temperatures of the front plate divided by the height of the radiator. The results show that turning and changing the distance ring geometry does not affect the mean segment temperature over the height.

HYDRAULIC CONNECTION OF RADIATOR

All previous mathematical simulations were created for a radiator model, which has one side connected to the top down, as was the case with the experiment. However, radiators are often connected to the heating system on both sides. Therefore, a mathematical simulation and comparison of the temperature and velocity fields for a distance ring with one hole (common) directed to the axis of the upper distribution chamber and the distance ring with the two holes in the ratio 03/10.

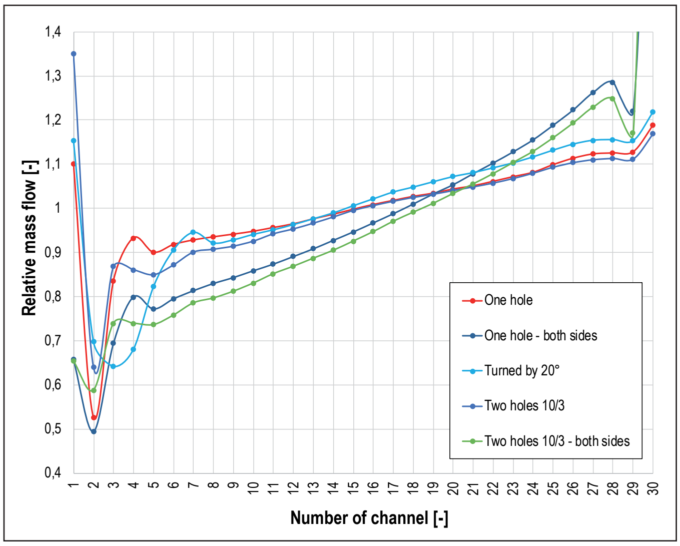

Fig. 6 Comparison of flow rates of individual radiator channels

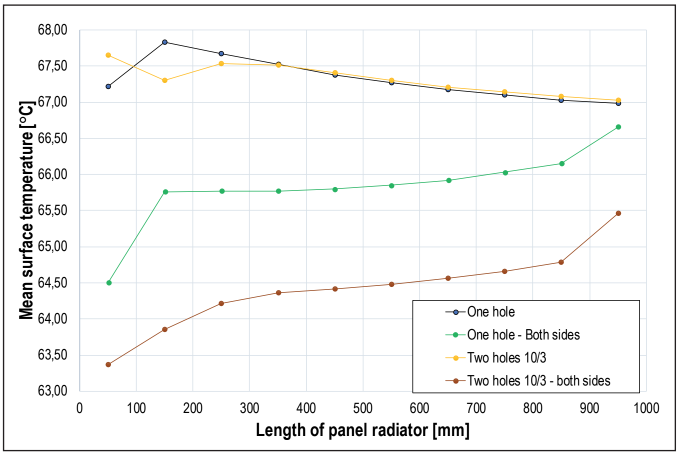

Fig. 7 Comparison of mean surface temperatures for individual sections along the radiator length

Figure 7 shows a comparison for the mentioned cases in one-sided and two-sided connection. With the same boundary conditions, mass flow rate and inlet temperature, the opposite direction of the mean surface temperature drop can be seen. Overall, these mean temperatures are lower and more in the left side of the radiator. This is due to the reduced flow rates of the channels in this section, as seen in Figure 6, where the flow rates are shown by individual channels for all the cases mentioned. Conversely, in the right part of the radiator, flow rates are higher, and even at the last channel being proportional to three times the flow rate (for clarity not shown in the graph).

CONCLUSION

In the overall comparison of Figure 5 shows that the most uniform temperature field along the length of the body is in the radiator with a distance ring with two holes. From the results of the velocity field in Figure 6, a higher flow rate in the second channel is seen compared to the ordinary distance ring model, which increased the surface temperature in this section. However, the flow rate is significantly increased through the first passage, which should be further reduced by adjusting the size or geometry of both holes. In the right part of the body, this flow without significant changes compared to the distance ring with one hole.

Two-sided connection leads to an overall change of flow inside the body. The flow rate in the left side of the body is significantly reduced and increased in the right side. The largest flow occurs in the last channel, which leads to the drain distance ring. This change in flow has a great effect on the temperature field. There is an overall decrease in mean surface temperatures in the compared sections along the length of the radiator.

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References

[1] BAŠTA, J. *Otopné plochy – otopná tělesa. 2. přepracované vydání.* Praha: České vysoké učení technické v Praze, 2016. ISBN 978-80-01-05943-2.
[2] LEGNER, T.; BAŠTA, J. Vliv natočení distančních kroužků v deskových otopných tělesech. I*n: Konference vytápění Třeboň 2017.* Třeboň: pp. 76-80. ISBN 978-80-02-02712-6.
[3] LEGNER, T.; BAŠTA, J. Vliv natočení a změny geometrie distančního kroužku u deskových otopných těles. In: *Simulace budov a techniky prostředí 2018 - sborník 10. konference IBPSA-CZ.* Praha: IBPSA-CZ, 2018, pp. 23-28. ISBN 978-80-907423-0-7
[4] LEGNER, T.; BAŠTA, J. Optimization of Distance Rings in Panel Radiators In: *Central Europe towards Sustainable Building (CESB19).* Bristol: IOP Publishing Ltd, 2019. IOP Conference Series. ISSN 1755-1315.
[5] JANČÍK, L., BAŠTA J. 2012 Dynamic behavior of panel radiators. Thermographic investigation and computer modeling of heat-up. 2012, EPJ Web Conf;25:02008-1–-6.

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Energy Balance of Compact Exhaust Air Heat Pump in a Single-Family House

Energetická bilance kompaktní větrací jednotky s tepelným čerpadlem v rodinném domě

The technology of exhaust air heat pump (EAHP) units and a brief classification of the products available on the market are presented in this paper. The performance of a compact EAHP unit providing exhaust air ventilation in a single-family house has been investigated. Due to the limited data provided by the manufacturers or by the 3rd party test reports, the laboratory testing of the EAHP unit has been performed. The data obtained from the test have been applied in the energy balance of the unit. A single-family house with a total heat loss of 5 kW was considered and the seasonal performance factor (SPF) achieved 2.5 for the given system with the compact EAHP.

Keywords: *exhaust air heat pump, ventilation, heat recovery, seasonal performance factor*

Článek představuje technologii kompaktních tepelných čerpadel využívajících odpadní vzduch a stručnou klasifikaci produktů dostupných na trhu. Předmětem zkoumání je konkrétní typ kompaktní větrací jednotky s tepelným čerpadlem zajišťující podtlakové větrání v rodinném domě. Kvůli malému množství dostupných dat z nezávislých testovacích protokolů nebo poskytovaných výrobci jednotek bylo provedeno laboratorní zkoušení. Získané parametry byly použity pro celoroční energetickou bilanci jednotky. Pro uvažovaný rodinný dům s celkovou tepelnou ztrátou 5 kW byl vyhodnocen sezónního topný faktor SPF celého systému na úrovni 2,5.

Klíčová slova: *kompaktní větrací jednotka s tepelným čerpadlem, větrání, rekuperace tepla, sezónní topný faktor*

INTRODUCTION

Nowadays, thermally well-insulated buildings have become a standard. The usage of high-performance envelopes, including windows, is emphasised and the importance of ventilation is slowly becoming an indivisible part of modern life. Ventilation systems with heat recovery from the exhaust air are also being used in single-family houses today. The question of heat recovery has been discussed since the 1970s already, especially in Scandinavian countries. Exhaust air heat pump (EAHP) units appeared as one option among all of them. The first EAHP units were only used for domestic hot water (DHW) preparation and with the function of space heating (SH) later on too. Today, compact EAHP units are mostly installed in northern countries, especially in Sweden and Finland. In 2018, more than 17 000 EAHP units were sold in Sweden, thus, sharing almost 30 % of the overall heat pump sales [2] and the share was around 90 % in new single-family houses [3]. Thanks to the favourable temperature of the indoor air, EAHP units have usually shown high efficiency values [4]. The operational conditions are relatively constant, which can positively affect the lifetime of the compressor used in the unit.

However, the topic of compact EAHP units is not a big issue in other European countries. An international standard for testing and evaluating the performance of EAHP units is still not available. The complexity of EAHP units also results in the fact that there is no common term for such types of heat pumps. The term EAHP is mostly used in northern countries and in English speaking countries. The German speaking countries from central Europe call it “heat pump ventilation compact units” or colloquially “compact units”. Finally, a universal and user-friendly tool for the evaluation of EAHP units in a specific installation for designers and building energy consultants is still missing today.

There are many different types of compact EAHP units with various designs, working with different temperatures at the evaporator and offering many functions. Different technologies of EAHP units are further listed. Specific EAHP unit devoted to a unidirectional exhaust air ventilation system has been further investigated from the point of view of its performance: laboratory testing, a simplified model development and energy balance calculation for a given single-family house. The energy balance has been undertaken using the bin method according to EN 15316-4-2 [1] with parameters derived from the laboratory testing.

EAHP UNITS

As mentioned before, there are many different types of EAHP units. In any case, the definition of EAHP units is fulfilled when the heat pump part is connected to the exhaust air path. Then, the EAHP units can be classified according to the following criteria.

- ☐ Heat source for the heat pump
  - Pure exhaust air
  - Mixed exhaust / outdoor air
  - Preheated air (e.g., ground heat exchanger)
- ☐ Distribution system
  - Air heating
  - Hydronic heating
  - Both possibilities
- ☐ Functionality
  - SH, DHW, ventilation
  - Optional cooling
  - Humidification
- ☐ Heat recovery exchanger
  - Included
  - Excluded
- ☐ Provided ventilation system
  - Balanced
  - Exhaust-only

Together, the last two points are the most interesting in the case of the EAHP efficiency evaluation. The presence of a heat recovery exchanger decreases the inlet temperature of the exhaust air at the evaporator and then the efficiency of the heat pump cycle is lower, but on the other hand, the heat exchanger improves the total energy balance of the ventilation. That is why the heat recovery exchanger must be included for, e.g., passive houses. In case of low energy buildings, retrofitting single-family houses or reconstructed flats EAHP unit with an exhaust-only ventilation system might be a solution. The cost of investments are significantly lower and the installation is much easier. An exhaust duct system can be situated in a very small space in the flat or house. The fresh air distribution is provided by a ventilation grid in the window frame or openable wall vents can be installed.

LABORATORY TESTING

A compact EAHP unit devoted to a unidirectional exhaust air ventilation system without a heat recovery exchanger has been investigated. The reasons for the choice were:

- the installation costs are lower when an exhaust duct system is installed only;
- the investment cost of the EAHP without the heat recovery exchanger with the exhaust fan only is lower as well.

The compact EAHP unit F750 from the Swedish manufacturer NIBE was chosen. The unit consists of a 180 l stainless steel DHW storage tank, a 35 l buffer tank for the SH, a 6.5 kW immersion electric heater, two circulation pumps and one exhaust air fan. Refrigerant R407c is used as the working fluid in the heat pump cycle. The declared heat output of the unit is 5.0 kW for the A20/W45 with an exhaust air flowrate 252 m^3/h at a maximum compressor speed.

The public data provided by the manufacturer are in accordance with European standards EN 14511-3 [6] or EN 14825 [7] in general. The points given especially by EN 14825 can hardly be used for the energy balance of the unit for a specific building, because the *SCOP* data and the power consumption are given for a building with a declared rated heat loss and no domestic water is considered in the *SCOP* evaluation. The data from the tests according to the conditions defined in EN 14511-2 [8] could be a good source for the further calculation and simulation with on/off heat pumps. Unfortunately, many manufactures do not publish detailed performance data (performance map) for different compressor speeds (frequency) and only some data are made public. It is not enough for development of the EAHP model. Third party independent certifications (e.g., HP KEYMARK or Q-label) do not provide the required data either.

In order to determine the detailed data on the heat output for the compact EAHP unit laboratory testing was performed in the laboratory of heat pumps at CTU UCEEB. The unit installed in the laboratory is shown in Figure 1. The principle scheme of the testing equipment is presented in Figure 2. The EAHP unit was placed into the laboratory climate chamber and connected to a hygrothermally conditioned space. The space heating loop of the EAHP unit was connected to a heat load circuit. The temperature difference at the condenser was controlled by an external speed-controlled circulation pump using a laboratory control system. The external air handling unit provided the air with the requested inlet dry bulb and wet bulb temperatures for the EAHP testing. The air flowrate at the evaporator was measured by a Sierra Nema mass flowmeter. The heating water flowrate at the condenser side was measured by a Siemens Sitrans Mag 5000 electromagnetic flowmeter. The temperatures were measured by Pt100 sensors. All the data for the performance evaluation were gathered by an ALMEMO data acquisition unit and by the control system of the laboratory. In order to evaluate the parameters of the refrigerant cycle, a ClimaCheck Performance Analyser was used.

Fig. 1 The EAHP unit in the laboratory

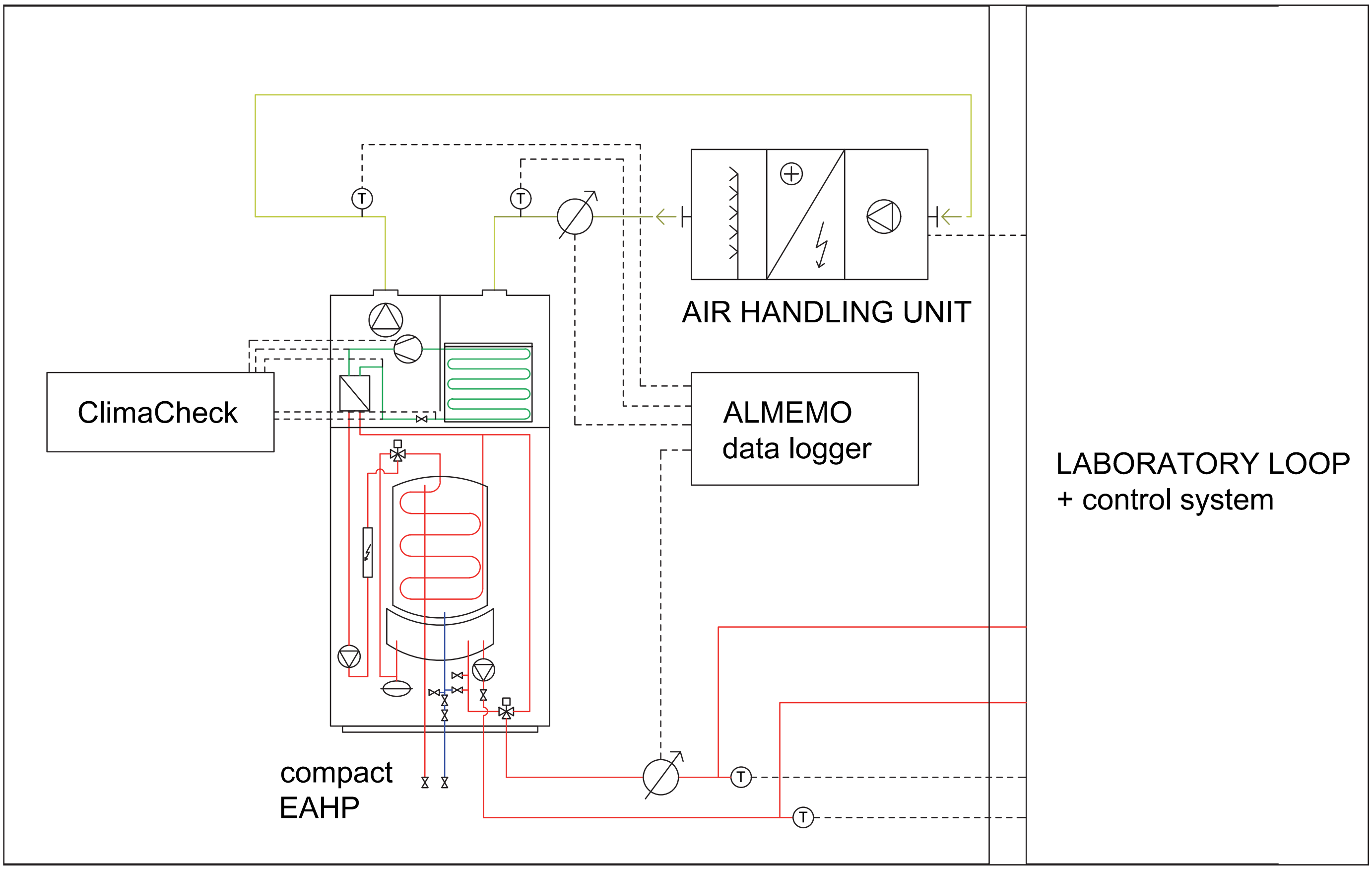

Fig. 2 The scheme of the EAHP testing

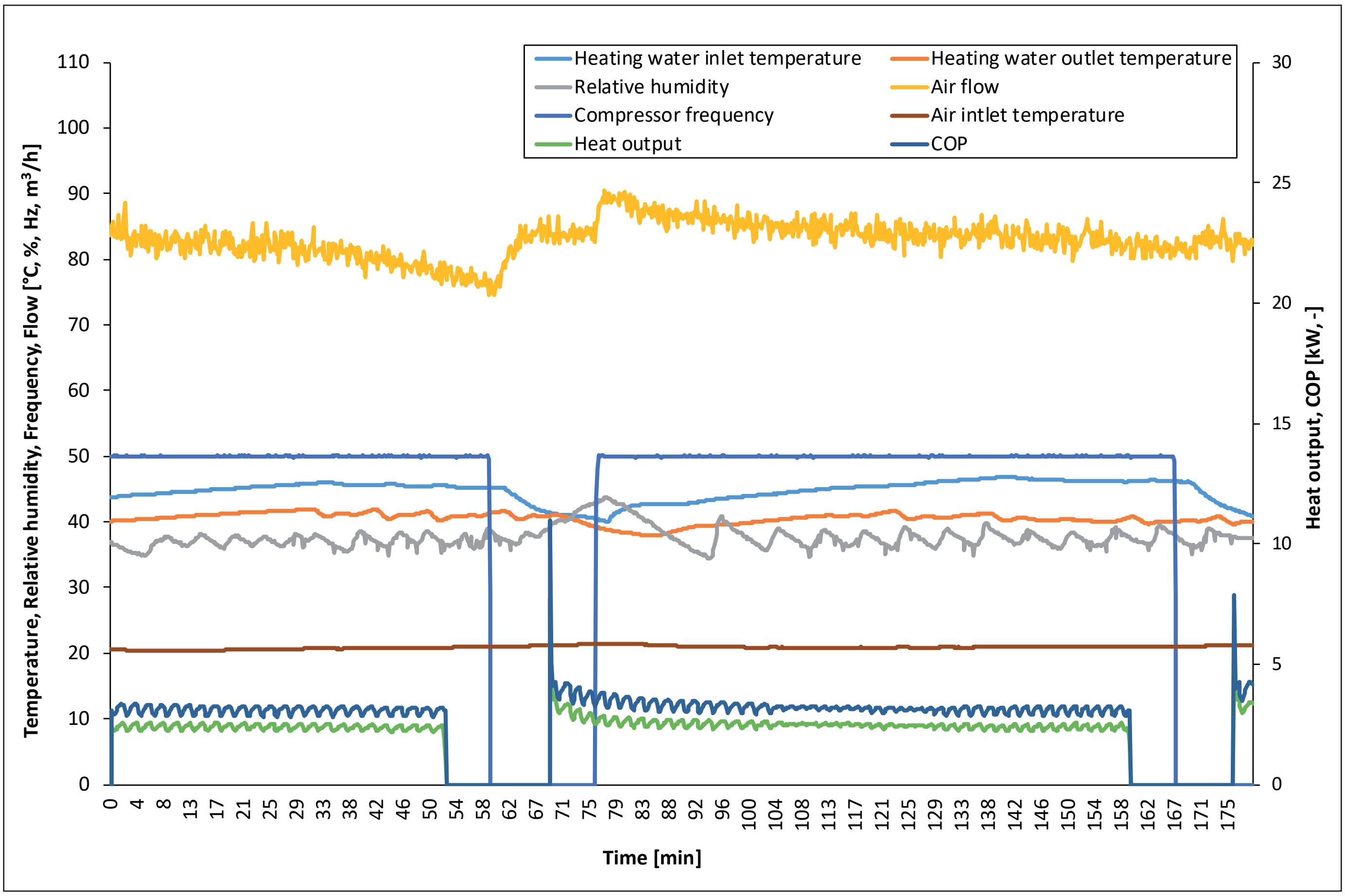

Fig. 3 A typical test cycle for the compact EAHP unit

Tab. 1 The performance data from the EAHP unit test for 240 m³/h

f_{HP} [Hz]	$\dot{V}_a$ [m³/h]	$T_{a,in}$ [°C]	$T_{a,out}$ [°C]	$\dot{V}_w$ [l/h]	$T_{w,in}$ [°C]	$T_{w,out}$ [°C]	E_{HP} [kW]	Q_{HP} [kW]	COP [-]
50	243	20.4	1.9	507	34.5	29.9	0.7	3.2	4.8
72	245	20.5	-7.9	698	35.5	29.9	1.1	3.7	3.5
50	243	20.3	6.0	581	45.2	40.0	0.8	3.6	4.4
72	238	19.4	3.3	749	45.4	40.1	1.0	3.9	4.1
50	239	18.9	6.5	580	54.0	50.1	0.9	2.8	3.0
72	239	18.5	0.9	686	55.4	50.6	1.4	3.9	2.8

The ClimaCheck unit measures the important values from the cycle, e.g., the condensing and evaporating pressure and temperature, the electric power input and provides the *COP* values of the cycle, refrigerant enthalpy, etc.

Different boundary conditions (test points) were set according to EN 14511-2 [8]. The exhaust air dry bulb temperature was 20 °C and the wet bulb temperature was 12 °C during the duration of the testing. The heating water temperatures at the condenser were maintained at 35/30 °C, 45/40 °C and 55/50 °C. The aim of the testing was to create a performance map with three different air flowrates – 80 (the minimum air flow required by the manufacturer), 180 and 240 m³/h and 4 different compressor frequencies: 25, 50, 72 and 100 Hz. Due to a large amount of test points, the testing periods were not fully in accordance with the test standard. However, at least 60 minutes of a steady state operation was required for each test point.

A typical test cycle is shown in Figure 3. Two defrosting cycles can be seen there. The air flowrate $\dot{V}_a$ [m³/h] decreases during the measurement. The flowrate depends on the frosting level at the evaporator and can decrease to 85 % of the original value. When the defrosting cycle starts, the heating water temperature decreases relatively quickly. Due to the heat output Q_{HP} around the value of 2.2 kW, it takes more than 70 minutes until a stable state is reached again.

The maximum heat output for 80 m³/h was 2.9 kW at the heating water temperatures of 55/50 °C and a frequency of 72 Hz. The *COP* reached 2.2 at the given conditions. It was not possible to test the EAHP unit at 100 Hz for the minimum air flowrate due to the evaporation temperature limit of -17 °C. The minimum heat output was 1.9 kW at W35/30 and 25 Hz with a $COP = 4.5$. Similar results for the higher air flows of 180 m³/h and 240 m³/h were obtained. The minimum heat output of 2.0 kW with a $COP = 4.5$ was reached for the flow of 180 m³/h at W45/40 and 25 Hz. The maximum heat output of 4.9 kW was reached at a 180 m³/h flow rate at W45/40 and 100 Hz with a $COP = 2.6$. An example of all the evaluated parameters for the air flowrate of 240 m³/h is presented in Table 1.

ENERGY BALANCE

To determine the annual performance of the compact EAHP unit in a single-family house, the energy balance according to EN 15316-4-2 [1] has been performed. The standard uses a bin method based on the frequency distribution of the ambient air temperature during the year. The energy balance is performed in temperature bins with the given temperature interval and duration of the ambient air temperature. As inputs for the bin method, the space heating and the hot water energy demand for the individual months are required together with a detailed performance map of the EAHP unit (frequency, heating water temperature).

A single-family house with a design heat loss of 5 kW (for an ambient air temperature of -12 °C and an interior air temperature of 20 °C) was chosen. A floor heating system was considered with the design heating water temperature difference of 35/30 °C and an equithermal control. The monthly space heating demand was calculated according to EN ISO 13790 [9] and the heat loss of the space heating system (distribution, emission) was considered to be 5 % of the theoretical heat demand. The annual heat delivered for the space heating Q_{SH} reached almost 12 MWh/a. In total, four people were considered with the DHW consumption of 40 l/day per person. The cold water temperature was 10 °C and the required tap water temperature was 55 °C. A hot water load decrease of 25 % during the summer months was also considered. The DHW energy demand was calculated according to EN 15316-3 [10] with a 30 % distribution heat loss. The heat Q_{DWH} delivered for

Tab. 2 The annual energy balance of the EAHP unit in the single-family house

Month	Q_{SH} **[kWh]**	Q_{DWH} **[kWh]**	Q_D **[kWh]**	Q_{HP} **[kWh]**	E_{HP} **[kWh]**	E_{SYS} **[kWh]**	COP_{HP} **[-]**	SPF_{SYS} **[-]**
January	1950	349	2299	1884	505	998	3.7	2.3
February	1662	315	1977	1669	450	829	3.7	2.4
March	1492	349	1841	1692	471	698	3.6	2.6
April	1054	337	1392	1392	410	484	3.4	2.9
May	613	349	962	962	324	387	3.0	2.5
June	0	337	337	337	171	186	2.0	1.8
July	0	262	262	262	132	144	2.0	1.8
August	0	262	262	262	132	144	2.0	1.8
September	576	337	913	913	311	376	2.9	2.4
October	1071	349	1420	1415	420	504	3.4	2.8
November	1488	337	1826	1633	455	723	3.6	2.5
December	1785	349	2134	1811	492	893	3.7	2.4
	11692	**3932**	**15624**	**14231**	**4272**	**6366**	**3.3**	**2.5**

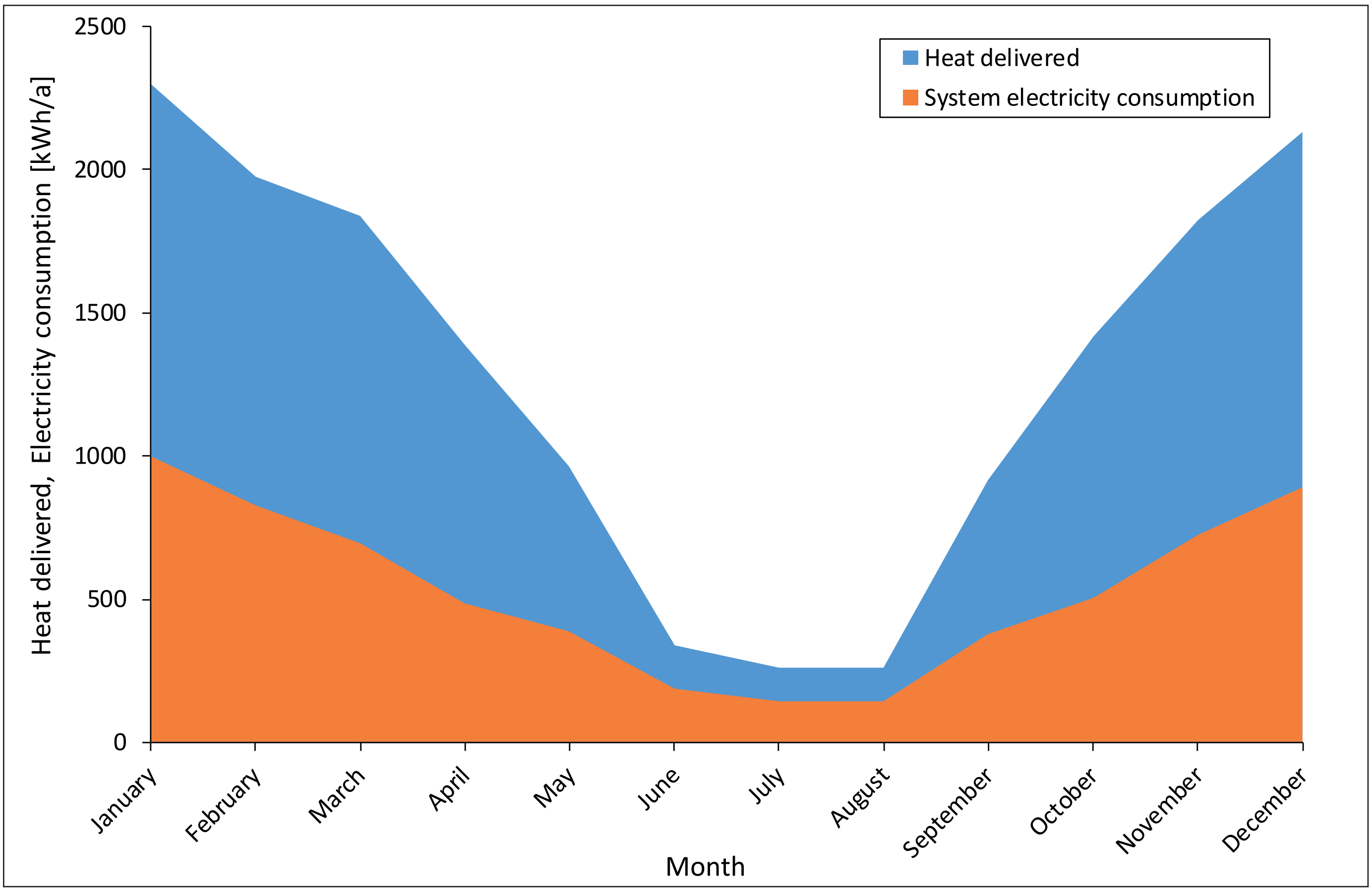

Fig. 4 The heat delivered to the house and the electricity consumption of the EAHP system

the DHW preparation results in a significantly smaller amount below 4 MWh/a were compared to the space heating.

The heat Q_{HP} delivered by EAHP unit itself covers about 91 % of the heat supply for the house, the rest is delivered by a backup electric heater. The total EAHP system electricity demand E_{SYS} includes the electricity consumption of the compressor, the unit's fans, the backup heater and the circulation pumps. The overview of the monthly energy balance is shown in Table 2. The comparison of the total heat delivered to the house with the electricity consumed by the EAHP system is presented in Figure 4.

CONCLUSION

An EAHP unit for a unidirectional exhaust air ventilation system without a heat recovery exchanger has been investigated. Due to the limited parameters available in the specifications for the modelling of the annual energy balance, detailed laboratory testing has been performed. The heat output and *COP* of the unit for the different temperature conditions, exhaust air flowrates and frequency of the compressor has been obtained. The annual energy balance of the EAHP unit operation in a single-family house based on the bin method has been evaluated. For the given example, the compact EAHP unit delivered about 91 % of the heat supplied by the system and the total *SPF* of the system resulted in 2.5. The EAHP unit performs with significantly better efficiency in the space heating application than for the domestic hot water preparation.

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References

[1] EN 15316-4-2. Heating systems in buildings – Method for calculation of system energy requirements and system efficiencies – Part 4-2: Space heating generation systems, heat pump systems. 2006.
[2] Svenska Kyl & Värmepumpföreningen, "Värmepumpsförsäljning," 2019. [online]. Available at: https://skvp.se/aktuellt-o-opinion/statistik/varmepumps-forsaljning. [Accessed: 12-Jan-2019].
[3] LINDHAL, HAGLUND STIGNOR, M., C., ANDERSON K., and THZBERG, S. Exhaust Air Heat Pumps Evaluated for Nordic Circumstances. In: *11th IEA Heat Pump Conference, 2014.*
[4] FRACASTORO, G., V., SERRAINO, M. Energy analyses of buildings equipped with exhaust air heat pumps (EAHP). *Energy Build.* 2010, vol. 42, no. 8, pp. 1283–1289.
[5] C. WEMHÖNER. *Calculation method for the seasonal performance of heat pump compact units and validation.* Luzern, 2007.
[6] EN 14511-3. Air conditioners, liquid chilling packages and heat pumps for space heating and cooling process chillers with electrically driven compressors - Part 3: Test methods. 2018.
[7] EN 14825. Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance. 2013.
[8] EN 14511-2. Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling - Part 2: Test conditions. 2018.
[9] EN ISO 13790. Energy performance of buildings — Calculation of energy use for space heating and cooling. 2008.
[10] EN 15316-3. Energy performance of buildings. Method for calculation of system energy requirements and system efficiencies. Space distribution systems (DHW, heating and cooling). 2007.

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Heat Pump Combined with PV for Single-Family House

Tepelné čerpadlo v kombinaci s fotovoltaikou pro rodinný dům

The simulation model of an energy system consisting of a ground-source heat pump combined with PV and thermal storage tanks for a single-family house was developed. The PV system is connected to the heat pump for the domestic hot water preparation and space heating. The energy system allows one to maximise the usage of the PV power by means of overcharging the volume of the storage tanks by the heat pump with the use of an adaptive control. Furthermore, a parametric analysis incorporating the different PV system power installed was carried out. With respect to the total electrical energy consumption of the heat pump, the annual grid consumption may be reduced up to 40 %.

Keywords: *heat pump, photovoltaics, nearly zero energy building, thermal storage*

Pro rodinný dům byl vytvořen simulační model energetického systému sestávajího z tepelného čerpadla země-voda kombinovaného s fotovoltaikou a akumulačními zásobníky tepla. Fotovoltaický systém je spojen s tepelným čerpadlem pro přípravu teplé vody a vytápění. Energetický sytém umožňuje maximalizovat využití výkonu fotovoltaiky přehříváním objemu akumulačních zásobníků tepelným čerpadlem prostřednictvím adaptivní regulace. Byla provedena parametrická analýza pro instalovaný výkon FV systému. Roční celková spotřeba elektrické energie ze sítě pro tepelné čerpadlo může být snížena až o 40 %.

Klíčová slova: *tepelné čerpadlo, fotovoltaika, téměř nulová budova, akumulace tepla*

INTRODUCTION

Implementation of the Directive on the Energy Performance of Buildings [1] into the national legislation has opened the question which energy systems for buildings could achieve the recommended figures for nearly zero energy buildings (NZEBs) [2]. As an ambitious target for the climate of the Czech Republic, the value of 20 kWh/m^2.a for non-renewable primary energy consumption can be set for space heating and hot water preparation.

The paper focuses on the heat pump system, which consumes electricity to transform low temperature heat into high temperature heat delivered in the building. Nevertheless, the electricity grid has a relatively high conversation factor for Europe in general and for the Czech Republic in particular (*PEF* = 3). Here, a combination of a heat pump system with photovoltaic (PV) technology is regarded as a logical step. On the one hand, feeding the energy produced by the local PV source into the grid has been complicated and has become less beneficial due to the negligible feed-in tariffs. Therefore, PV installations today are oriented to maximise its self-consumption. On the other hand, the time periods of the PV and heat pump's operation do not naturally match. The PV system generates electricity during the day and the summer season, the heat pump operates mostly during the winter, at night and in the morning/evening during the hot water load peaks.

From the available alternatives on how to overcome this mismatch (e.g., demand-side management), a load-shifting method was adopted in this paper. To arrive at the most cost-effective system operation, the surplus PV power is transformed by the heat pump and is stored in storage tanks by means of overcharging (charging a larger part of the tank volume at high temperature). Subsequently, such a strategy forces the heat pump to operate when the PV power is produced, i.e., it shifts the heat pump consumption towards the daylight hours.

HEATING SYSTEM

The energy system is represented by the heat pump operating with two storage tanks: 300 litres for the domestic hot water (DHW) preparation and 450 litres for the space heating (SH). Then, the heat for the space heating is distributed through the floor heating system with nominal heating water temperatures of 35/30 °C. The supply temperature to the floor heating system is set by the heating curve. The DHW demand profile is 206 l/day with a water intake temperature of 45 °C. The DHW heat demand is 3060 kWh/a, the SH demand is 4300 kWh/a.

The heat pump nominal output is 5.7 kW and the *COP* (coefficient of performance) is 4.6 at the B0/W35 condition. A simplified scheme of the heating system is shown in Fig. 1. The whole system has a controller logic as follows:

- ☐ the heat pump starts with respect to the conventional control signal (the temperature sensors are installed at the upper part of the tanks at 70 % of the tank's height), the strategy hereinafter is referred to as *non-PV-led* (see the upper part of Fig. 3);
- ☐ the previous signal is modified: the heat pump also starts when the PV power is higher than the threshold power and overcharges the storage tanks (additional sensors are installed at the bottom lower part of the tanks at 10 % of the tank's height), however, the sensor in the upper part still has the priority. The strategy hereinafter is referred to as *PV-led* (see the bottom part of Fig. 3);
- ☐ the threshold power was defined for the heat pump on a priori for the simulation of an on/off compressor.

As seen from the Fig. 1, two temperature sensors are employed for the control purposes. The setpoints for the DHW are 50 °C for the top sensor (standard operation) and 55 °C for the bottom sensor (overcharging operation). For the SH storage tank, the top sensor setpoint is the heating curve supply temperature plus 2 K, the bottom sensor setpoint is 55 °C.

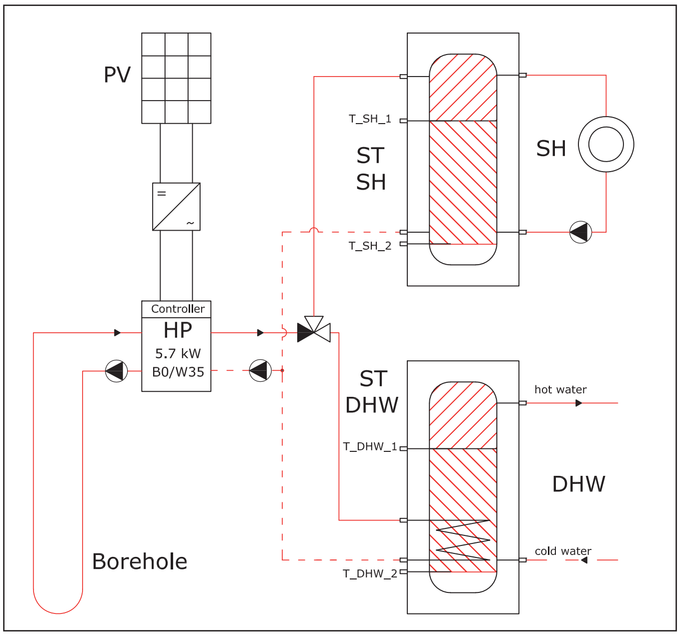

Fig. 1 The scheme of the PV heat pump system

FAMILY HOUSE

The single-family house (built in 2016) shown in Fig. 2 has been employed in the research. The building is situated in the Czech Republic and its design heating loss is 4.5 kW at -12 °C ambient temperature. The total heated area is 286 m^2 while the volume is around 1000 m^3. The building is heated by a floor heating system. The building is equipped with a PV system of 6 kW$_p$, however, a series of the installed PV power was studied, i.e., 1, 3 and 6 kW$_p$. The roof slope (PV modules slope) is 40^o.

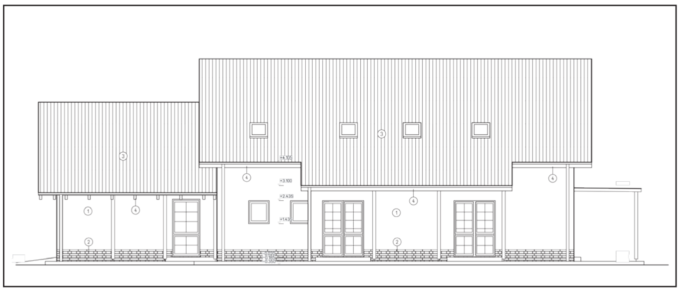

Fig. 2 The family house used in the case study

SIMULATION ANALYSIS

The PV heat pump system was described with the Modelica language and Buildings library use [3]. The heat pump model used is a grey model which considers a simplified compressor cycle. The storage tanks are modelled considering stratification. The PV system is a 5-parameter model that takes the optical and electrical properties of the module into account. The borehole is 75 m deep [4] in the ground with average properties (conductivity 2 W/m.K). The building envelope was described using the IDEAS library [4], the U-values of the constructions are as follows:

☐ Walls – 0.12 W/m^2.K;
☐ Floor and ceiling – 0.15 W/m^2.K;
☐ Windows – 0.7 W/m^2.K.

The weather conditions used in the simulations are those typical for meteorological year [5] in Prague.

RESULTS

A heat pump system with a borehole for the SH and the DHW was modelled as a reference case. Such a system has a seasonal performance factor (*SPF*) of 3.73, the total electricity consumption of the system is 1976 kWh. If the PV system of 6 kW$_p$ is added to the heat pump system then the *SPF* results in 4.9 (Tab. 1). The PV-generated power used for covering the electricity hardly approaches a value of 470 kWh even though the PV modules generate 5420 kWh annually. Thus, the PV power usage is extremely low – around 9 %. Moreover, the specific nPE demand results in a value of 24 kWh/m^2.a, thus, it is still above the target set. The following research f°Cuses on the measures for the specific nPE demand decrease in the respected energy system.

Furthermore, the same system was studied with a conventional control strategy with respect to the PV power (non-PV-led) and with an advanced control strategy (PV-led) with a series of PV installed power of 1, 3 and 6 kW$_p$. The results are presented in Tab. 1 and Tab. 2.

Tab. 1 – The simulation results for the conventional control strategy (non-PV-led)

Parameter	**w/o PV**	**1 kW$_p$**	**3 kW$_p$**	**6 kW$_p$**
Electrical power need [kWh/a]	1976	1874	1673	1504
System *SPF* [-]	3.73	3.94	4.41	4.90
Solar fraction f_{PV} [%]	-	5	15	24
Solar usage r_{PV} [%]	-	12	11	9
Specific nPE consumption [kWh/m^2.a]	31	30	26	24

Each installed power of the PV system results in its own optimum threshold power level – the value of the PV system generating power above which the heat pump is started to overcharge the storage tanks. In addition, the results are presented in Fig. 4 as a graph of the external electricity grid needed versus the power threshold. Based on these results, it is worth noticing that the grid electricity needed for the system studied is also in high dependence on the thresh-

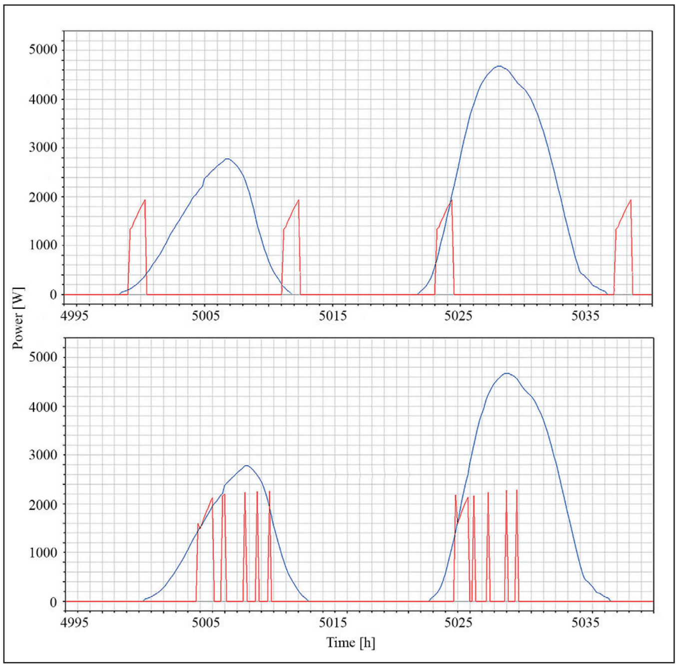

Fig. 3 The simulation results for the non-PV-led system (on the left) and the PV-led system (on the right) (the PV power is in blue and the heat pump power is in red)

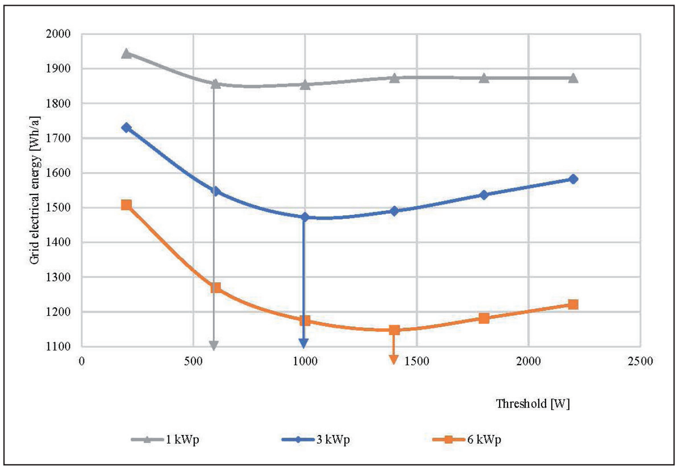

Fig. 4 The optimum power threshold levels for the given PV peak power installed

old, which also takes place with the heat pump-PV system for the DHW preparation only. Nevertheless, the optimum threshold values can be derived from the graph: as the PV power installed increases the threshold, the level increases as well (see Fig. 4): for 1 kWp, the threshold was found at 600 W, for 3 kWp at 1000 kWp and for 6 kWp at 1400 W. The results in Tab. 1 and Tab. 2 are given considering these optimum values for the the threshold power.
During the extensive number of simulations, the heat pump operated under the on/off controller only and the results in Tab. 1 - 2 are given for the on/off heat pump.

As follows from Tab. 2, the specific nPE system consumption can be reduced up to 18 kWh/m^2.a by introducing a PV-led control approach. With this improvement, the specific nPE demand meets the set target of 20 kWh/m^2.a.

CONCLUSION

Overall, there are several approaches aimed to reach the NZEB target energy demand. In parallel to these approaches, a clear and sustainable way is to use a heat pump combined with the PV and PV-led strategy employed. This paper investigates the operation of the energy system consisting of a ground-source heat pump combined with PVs and a thermal storage for a single-family house. Furthermore, the specific nPE need of the house is 18 kWh/m^2.a (for the SH, DHW and auxiliary energy) which is in good accordance with the target NZEB demand set in this article. The study brought the benefits of a heat pump-PV system to light, consequently the nPE demand is reduced up to 42 % with 6 kW$_p$ PV compared to the reference system. Moreover, the PV-led strategy decreases the electricity grid demand by 12 % and by 24% compared to the conventional (non-PV-led) control approach for the 3 and 6 kW$_p$ PV systems, respectively.

Tab. 2 – The simulation results for the advanced control strategy (PV-led)

Parameter	**w/o PV**	**1 kW$_p$**	**3 kW$_p$**	**6 kW$_p$**
Electrical power need [kWh/a]	1976	1857	1473	1148
System *SPF* [-]	3.73	3.97	4.96	6.41
Solar fraction f_{PV} [%]	-	8	30	46
Solar usage r_{PV} [%]	-	19	23	18
Specific nPE consumption [kWh/m^2.a]	31	29	23	18

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LITERATURE

[1] E. Parliament and Council. European Directive on Energy Performance of Buildings. 2010.
[2] Commission Recommendation (EU) 2016/1318 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings. 2016.
[3] M. WETTER, W. ZUO, T. NOUIDUI, and X. PANG. Modelica Buildings library. *J. Build. Perform. Simul.* 2014, vol. 7.
[4] F. JORISSEN, G. REYNDERS, R. BAETENS, D. PICARD, D. SAELENS, and L. HELSEN. Implementation and verification of the IDEAS building energy simulation library. *J. Build. Perform. Simul.* 2018, vol. 11, no. 6, pp. 1–20.
[5] Building Technologies Office. Department of Energy. EEUU, 2016 [online]. Weather Data for Simulation EnergyPlus. Avilable from: *www.energyplus.net*

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Testing of Pilot Buildings by the SRI Method

Testování pilotních budov metodou SRI

The paper deals with the issues of the Smart Readiness Indicator (SRI), which describes buildings in terms of their intelligent systems. In first part, the principles of SRI and the processes of a building's assessment are explained. The second part contains a case study of four buildings in the Czech Republic with different technical systems and the Smart Readiness Indicator is calculated for them.
Keywords: *Smart Readiness Indicator, Intelligent Buildings*

Článek se zabývá tzv. Indikátorem připravenosti budov na chytrá řešení (Smart Readiness Indicator, SRI), který popisuje úroveň inteligence budov a jejich systémů. V úvodní části článku jsou popsány principy SRI a procesy, jak budovy hodnotit. Druhou částí článku je případová studie 4 budov v České republice s různými technickými systémy, pro které je proveden výpočet indikátoru.
Klíčová slova: *Smart Readiness Indicator, inteligentní budovy*

INTRODUCTION

The revised European Energy Performance of Buildings Directive (EPBD) supports smart building technologies, but the question, how to describe the "smartness", has arisen. The European Commission has assembled a consortium of experts accordingly. This consortium put together a so-called Smart Readiness Indicator (SRI) which describes how the building is prepared for smart systems, which can ensure the indoor environmental quality, energy performance, convenience and other parameters of a building's operation.

The SRI is a percentage of the real level of smart systems according to the maximal achievable conditions in an assessed building. The total SRI score is calculated from the impact scores and domain scores by weighting each impact/domain. The term impact score means how the fields of a building's use are equipped by smart ready technologies, the domain scores are focused on a building's technical systems and their "smartness".

THE PROCESS OF A BUILDING'S ASSESSMENT

At first, the general information of an assessed building is defined:
- ❑ Building type (residential, non-residential),
- ❑ Building usage (for residential building, e.g. Single-family house, large multi-family house etc., for another type, e.g. Educational, office building, etc.)
- ❑ Location in climate zone (European Union is divided into five zones)
- ❑ Net-floor area
- ❑ Year of construction
- ❑ Building state (original, renovated)
- ❑ Building domains (technical systems) present (heating, domestic hot water, cooling system, controlled ventilation, lighting, dynamic envelope, electricity: renewables and storage, electric vehicle charging, Monitoring & Control)

Then, for each building domain, the type of technical system is defined. For example, each heating service has its own emission type (TABS, hydronic or non-hydronic system), production type (district, central, decentral heating, heat pump), presence of energy storage and number of heat generators. Thereafter, each domain has its services. The maximum number of services is 52, but the real number depends on presence of the domains and their type.

Each service has its own impact and domain weighting according to the functionality level, climate zone and building usage. The functionality level is a description of the service and marked by a number. The number 0 means a simple system with nothing smart and a higher number means a smarter service. Some services have their maximum at functionality level 2 (for example detecting faults of the technical systems and their diagnostics), or the maximal functionality level is 4 (for example heat control on the demand side).

The final SRI score is calculated from these parameters and their impacts. The score for a single impact parameter is a percentage of the real score versus the maximum which can be achieved. The total SRI score is a percentage of the sums of the scores for each impact to the maximal achievable score.

The impact scores which make up the total SRI score together, are:
- ❑ Energy savings on site
- ❑ Flexibility for the grid and storage
- ❑ Comfort
- ❑ Convenience
- ❑ Wellbeing and health
- ❑ Maintenance and fault prediction
- ❑ Information to occupants

The domain scores are calculated for each domain (technical system) which is installed in the assessed building.

CASE STUDY

The case study contains the SRI assessment of four different buildings in the Czech Republic. Each building has a different level of smart services.

Building 1 – A family house in Všenory

The first case is a small renovated family house located in the Central Bohemian region. It is a stone-structure, combined with a newer extension of aerated concrete. It is a traditional non-smart family house built in the early 19th century and only equipped by electrical heating (accumulation stoves) and electrical hot water preparation in a water tank. The lighting is a classic system as well (on/off switches). The charging of the stoves has a timetable connected to the switching to a cheaper tariff (8 hours per day). The renovation took place in the 2000s and 2010s.

Fig. 1 Building 1 – the family house in Všenory (source: www.mapy.cz)

Building 2 – An apartment block in Praha-Suchdol

Another residential building is an apartment block located in the outskirts of Prague. It is a large multi-family house of a prefab concrete structure built in the 1980s and renovated in the 2000s. As in the previous case, the building has heating, domestic hot water preparation and lighting. The heat source is a gas boiler, which prepares the domestic hot water as well. The heating system is a hydronic system with radiators and is controlled by the outside temperature (equithermal regulation). The DHW (domestic hot water) has its own schedule of charging the water tank. The lighting is similar, the HVAC (heating, ventilation and air conditioning) system is simple with the indication of detected faults and alarms.

Fig. 2 Building 2 – the apartment block in Praha-Suchdol (source: www.mapy.cz)

Fig. 3 Building 3 – Building A of the Faculty of Civil Engineering (source: cs.wikipedia.org)

Building 3 – The Faculty of Civil Engineering, CTU in Prague, Block A

It is the only non-residential building in this case study. The building is a 15-storey building located in Prague-Dejvice, built in the 1970s and renovated in the 2010s. This building is supplied by district heating as the only heat source for both the heating and DHW preparation. Part of the building is equipped by controlled ventilation (air-handling units). The exposed south/west facade has movable motorised shades reacting to the solar irradiation. Each room has its own heat control, the distribution of the heat is in accordance with the outside temperature. The heating system is hydronic. Some parts (corridors) have the occupancy control for lighting.

Tab. 1 The description of the buildings and their technical systems

	Building	Building 1	Building 2	Building 3	Building 4
GENERAL INFORMATION	Building type	Residential	Residential	Non-Residential	Residential
	Building usage	Single-family house	Large multi-family house	Educational	Single-family house
	Net-floor area (m²)	<200	1.000-10.000	>25.000	<200
	Year of construction	<1960	1960-1990	1960-1990	>2010
HEATING	Emission type	Non-hydronic	Hydronic (radiators)	Hydronic (radiators)	Hydronic (radiators)
	Production type	Decentral	Central	District	Decentral
	Thermal Energy Storage	Yes	No	No	No
	Multiple heat generators	No	No	No	Yes
DOMESTIC HOT WATER	Production type	Electric	Non-electric	Non-electric	Combination
	Storage present	Yes	Yes	Yes	Yes
	Solar Collector	No	No	No	Yes
CONTROLLED VENTILATION	System type	No	No	Controlled natural ventilation (10% of the building)	No
DYNAMIC ENVELOPE	Movable shades	No	No	Yes	No

Fig. 4 Building 4 – The family house in Rýmařov (source: Kabele, Urban: Grant no: te02000077 Smart Regions – buildings and settlements information modelling, technology and infrastructure for sustainable development)

Building 4 – A family house in Rýmařov

The fourth case is a family house located in the Moravian-Silesian region in the Jeseníky mountains. It is a newly built wooden one-storey structure with a currently non-occupied attic. The main heat source is a stove where pieces of wood are burnt. The stove is connected to the hydronic heating system. There is also an electrical boiler as a backup source, which is connected to the heating system as well. The DHW is prepared in a water tank, whose main heat source is the above-mentioned heating system, heat is tranfered by heat exchanger inside the tank. There is another heat exchanger connected to a circuit with solar collectors. Third back-up source is an electric heat cartridge. The heat emission is controlled room by room, the DHW is controlled in accordance with the solar energy supply. All energy flows are measured and the data are collected for the indication of any changes. So, the HVAC system has a central reporting of the technical building system performance and the energy use.

Tab. 1 above describes all the different input parameters of the buildings. All the buildings are in the Czech Republic, so the climate zone for the SRI assessment is North-East Europe.

In the field of technical systems, no assessed building is equipped by cooling, renewable electricity source or electric vehicle charging.

SRI CALCULATION

This chapter includes the results of the SRI calculation for all four buildings. The total SRI score and the single impact scores are shown in Tab. 2. Tab. 3 describes the domain SRI score.

Tab. 2 The total SRI score and the impact SRI score assessment

Building	Building 1	Building 2	Building 3	Building 4
Total SRI score	**14%**	**28%**	**35%**	**37%**
Energy savings on site	17%	31%	43%	52%
Flexibility for the grid and storage	31%	35%	36%	12%
Comfort	9%	34%	39%	51%
Convenience	5%	29%	30%	39%
Wellbeing and health	0%	100%	31%	100%
Maintenance & fault prediction	0%	12%	25%	32%
Information to occupants	0%	13%	18%	31%

The results shown in Tab. 2 say that Building 4 has the best total SRI score. Building 1 has the worst score, which is as expected, as it is equipped by a classic technical system only. The number is increased partly thanks to the flexibility of the heating system to the grid. Building 2 is a common apartment block type. In can be estimated that many apartment blocks in the Czech Republic can reach a similar SRI score. Building 3 is strong in the energy savings because of the shading control. The shading increases the comfort of the building. Building 4 is designed as a low-energy house, so the energy savings on site have the highest score, but there is low flexibility to the grid.

In Table 2, one peculiarity can be observed: The 100% impact score of the Wellbeing and health. The reason is that only the two HVAC services have influence on the Wellbeing and health assessment. The maximal score is reached in the case of the presence of any functionality, not in the case of the functionality level.

Tab. 3 The domain SRI score

Building	Building 1	Building 2	Building 3	Building 4
Heating system	26%	36%	55%	39%
Domestic hot water	29%	12%	34%	57%
Cooling system	-	-	-	-
Controlled ventilation	-	-	4%	-
Lighting	0%	0%	10%	0%
Dynamic envelope	-	-	38%	-
Electricity: renewables & storage	-	-	-	-
Electric Vehicle Charging	-	-	-	-
Monitoring & Control	0%	25%	27%	32%

The most interesting, in terms of the domain score, is Building 3, which is equipped by more technical systems than the other buildings. As only a part of the building has controlled ventilation, only a 4% score of the Controlled Ventilation domain was reached. The dynamic envelope only contains an automatic shading system, not the control of a window's opening or performance information reporting, so the score is "window opening" 36%. Building 4 has the highest DHW score because of the renewable energy source present.

CONCLUSION

The Smart Readiness Indicator provides simplified, but good information about the technical building systems in terms of their smartness. The calculation has some shortcomings. For example, it is impossible to define two different heat sources (e.g. hydronic heat systems combined with a fireplace). Some impact score calculations are insufficient, so the Wellbeing score can easily reach 100 % because there are a small number of services which have an impact on this score.

It is difficult to reach 100 % of the total SRI score because such buildings would have very sophisticated intelligent systems, which can be expensive and sometimes be non-user friendly. On the other side, the assessed buildings have a big potential to improve their parameters in terms of smart readiness.

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References

[1] Directive (EU) 2018/844 of the European Parliament and of The Council of 30 May 2018 amending Directive 2010/31/EU of the energy performance of buildings and Directive 2012/27/EU on energy efficiency [online]. Copyright © [cit. 14.11.2019]. Avilable from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN

[2] Smart Readiness Indicator for Buildings | Smart Readiness Indicator for Buildings. Smart Readiness Indicator for Buildings | *Smart Readiness Indicator for Buildings* [online]. Avilable from: https://smartreadinessindicator.eu/

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Energy Consumption, Operation and Commissioning of Buildings

Spotřeba energie, provozování a commissioning budov

The issue of energy consumption is becoming the main topic in many fields. Buildings that consume over 40 % of all the primary energy in developed countries, together with a significant contribution of CO_2 emissions [1], currently receive a considerable amount of attention. The paper deals with the issue of energy consumption of HVAC systems of buildings during their real operation and with process of their commissioning. The commissioning is solved both in general terms and as a mean of achieving the correct and energy efficient operation of buildings. Special attention is paid to the situation in the Czech Republic.

Keywords: *Building energy consumption, commissioning, building operation*

Problematika spotřeby energie se stává v posledních letech ústředním tématem v mnoha oblastech. Budovám, které ve vyspělých státech spotřebovávají přes 40 % veškeré primární energie spolu s významným podílem na emisích CO_2 [1], tak momentálně náleží značná pozornost. Příspěvek se zabývá problematikou energetické spotřeby technických systémů budov při jejich reálném provozu a commissioningem, a to jak v obecné rovině, tak jako prostředkem pro jejich správný a energeticky efektivní provoz. Zvláštní pozornost je věnována situaci v České republice.

Klíčová slova: *spotřeba energie budov, commissioning, provozování budov*

INTRODUCTION

The environmental and political aspects of the efforts to minimise the European Union's dependence on fossil fuels is a significant driving force leading to pressure to reduce energy consumption and the use of renewable sources. According to the Energy Performance of Buildings Directive (EPBD) 2018 [2], buildings in the European Union are responsible for 36 % of CO2 emissions and for almost 50 % of the energy consumption used for heating and cooling, of which 80 % is in buildings. This puts the minimisation of the energy consumption together with the maximum possible decarbonisation of the building stock at the forefront of the current European Union priorities in the area. In technical practice, we are increasingly meeting stringent requirements for both the thermal properties of building materials and the ever-increasing requirements for the energy efficiency of heat and cooling sources and other building technical equipment. However, only little attention is paid to how these technologies are operated and whether they actually work in an energy-efficient way, as was intended in their design, despite the fact that many studies [3], [4], [5] prove that not only the design, but also the correct operation of these systems has a major impact on the energy consumption.

The existing Czech legislation in this area is also still inadequate, although the new EPBD 2018, partially addresses the real operation of buildings and it can be expected that some measures aimed at the energy efficient real operation of buildings will be adopted within its implementation. Also, the phase of putting a building into operation does not actually help to solve the optimal operation of the technical systems. This part of a building's life-cycle is very often reduced to the verification of the principal functionality of the systems and the ability to achieve the required indoor environment level only. However, it should be noted that the ability of a technical system to provide the required microclimate conditions in a building does not necessarily mean that the system is operated optimally, i.e., with the minimum energy consumption while maintaining the required interior comfort level. Thus, the potential of advanced technologies and the sophisticated design of the entire system at the design stage may not be properly utilised in the real building operation.

The aim of this paper is to point out the problematic areas associated with the real operation of buildings and answer the question whether this issue is truly actual and whether it is expedient to spend energy in an effort to optimise their operation. Furthermore, this article deals with the method of a building's commissioning. First, it deals with this often incorrectly understood concept in general, then as a “tool” for the energy efficient and sustainable operation of a building.

ENERGY CONSUMPTION OF BUILDINGS IN REAL OPERATION

For the purposes of the objective evaluation of the real operation of buildings in the Czech Republic, it is generally very difficult to obtain any relevant data. Unfortunately, the detailed monitoring of the operation, analysis of the historical data and its evaluation are still the exceptions. This contribution, thus, partly follows up on the article “Reducing Energy Consumption for Air-Conditioning by Commissioning and Optimized System Operation” [6] which analysed the real energy consumption of the cooling sources of fifteen buildings situated in Czech Republic over the course of five years of their operation. One of the conclusions of this paper was the finding that the energy consumption for cooling per square meter of air-conditioned area was fundamentally different even within buildings with the same use (office buildings) as can be seen in Fig. 1. The detailed analysis showed different approaches in the operating strategy of the cooling sources and dramatic changes in the consumption for two buildings after the change of the management company, which operated the technical systems of the buildings. These findings observed on the analysed building sample, led to the conclusion that buildings are not operating efficiently in terms of energy consumption and that detailed monitoring is essential to optimise their operation.

The situation elsewhere in the world is illustrated by the outputs from several large-scale projects. In Europe, for example, a very large iServ

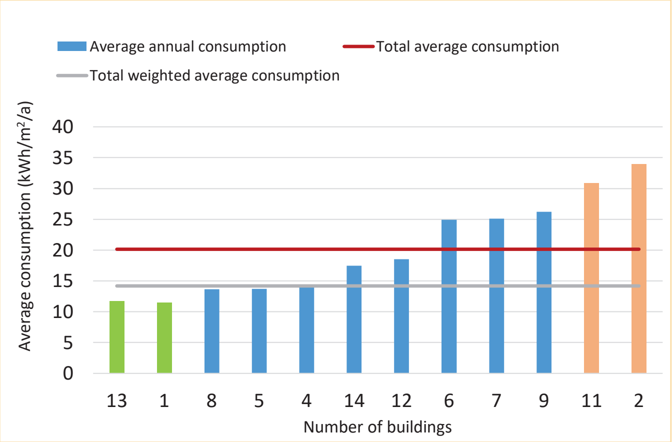


Fig. 1 The average annual consumption of office buildings

project was devoted to energy consumption in buildings, specifically to HVAC systems, which took place between 2011 and 2014. With a budget of over 3 million Euros, this project has mapped 2831 HVAC systems in 330 buildings across 16 European Union countries through continuous measurement and benchmarking. The aim of this project was, among other things, to highlight the importance of consumption monitoring, which can provide feedback from a building's operation and give the possibility to take energy saving measures. By applying this approach, the buildings involved in the project have achieved an average electricity savings of over 9 %. For some buildings, the savings were even 33 %. The author of the project states that applying this approach across Europe could save between 0.3 % and 5 % of the total electricity consumption across the EU and savings of over 20 billion Euros per year could be achieved at a cost of only about 1-3 billion Euros.

In general, most studies or research which deals with the energy consumption of buildings in their real operation, comes with a common conclusion, that most buildings are not functioning properly, and by optimising their operation, significant energy savings can be achieved.

ENERGY PERFORMANCE OF BUILDINGS DIRECTIVE - EPBD 2018

The main legislative document dealing more comprehensively with the energy consumption of buildings is the Energy Performance of Buildings directive (EPBD). Within the national implementation of this directive from 2002 and 2010, the energy performance certificates of buildings (Decree No 148/2007 Coll.) and the so-called reference building for the calculation of reference values in the calculation of the energy performance certificate of buildings (Decree No 78/2013 Coll.) were introduced [7]. However, only the current 2018 directive, which is to be implemented by 10 March 2020, deals more strongly with the consumption of buildings in real operation. [2]

The Directive now places great emphasis on existing buildings. The text appeals to the need to renovate the existing building stock and "transform" it into nearly zero-energy buildings and achieve a greenhouse gas emission reduction of 80 to 95 % by 2050. The directive no longer deals with the energy consumption of buildings only, but also addresses the issues of a healthy indoor environment. Saving measures should, therefore, be comprehensive and not only address the building envelope, but also the technical systems, with the aim of reducing energy consumption while increasing the visual and thermal comfort.

The directive further states the findings concerning the lack of effectiveness of the method of inspection of HVAC systems as they "do not ensure the initial or continuous economy of such technical systems". According to the directive, the aim of carrying out inspections should be to improve the energy performance of the HVAC systems under real operating conditions. Emphasis is placed on the ability of the systems to increase their performance under dynamically changing conditions, such as partial load operating conditions, where the system only operates with part of its nominal power. The possibility of replacing inspections by building automation and electronic monitoring of building technical systems is also listed. Building automation and control are even considered, in the case of large, non-residential buildings with large systems, as the most cost-effective alternatives to inspections with the serious potential for cost-effective and significant energy savings.

The new Directive places a great deal of emphasis on automation, as it is required to equip non-residential buildings above an effective rated heating or combined heating and ventilation system output of 290 kW with a building's automation and control systems by 2025. It states, in detail, that these buildings' automation and control systems will be able to:

- Continuously monitor and analyse the energy consumption and to enable its regulation
- Compare the energy efficiency of a building by reference, identify the losses in the performance of the building's technical system and to inform about possibilities how to improve the energy efficiency
- Enable communication with the building technical systems and other appliances it the building, as well as interoperability with the building technical systems that includes equipment from different manufacturers

Increased pressure towards reducing the consumption of buildings in their real operation is certainly a positive step. However, how specifically the Directive will be implemented in the national laws and regulations and what these methods and requirements will actually mean in practice is now only a question.

COMMISSIONING

Commissioning (Cx) is a term, which is still not widely publicised and correctly understood in the Czech Republic, but also, in many other countries and often even among the professional public. Often, the interpretation of commissioning can be seen as a process of "putting a building into operation". That is, the phase after constructing the building and before handing it over to the investor to just verify its basic functionality. However, this interpretation is slightly misleading, because Cx is a much broader term and "putting a building into operation" is only part of it according to the generally accepted interpretations and definitions of this term.

A building commissioning is a systematic process of managing the quality of the design, construction and operation of the building and its systems [8]. Cx ensures that the building has met the investor's needs and requirements and that it works efficiently energy-wise. The definition of commissioning according to the IEA (International Energy Agency) Annex 40 [9] characterises commissioning as: "a quality-oriented process for achieving, verifying, and documenting whether the performance of a building's systems and assemblies meet defined objectives and criteria". This internationally established definition is very close to the one used by ASHRAE (The American Society of Heating, Refrigeration and Air-conditioning Engineers) Standard 202 and Guideline 0, which defines Cx as "A quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that all of the commissioned systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements."

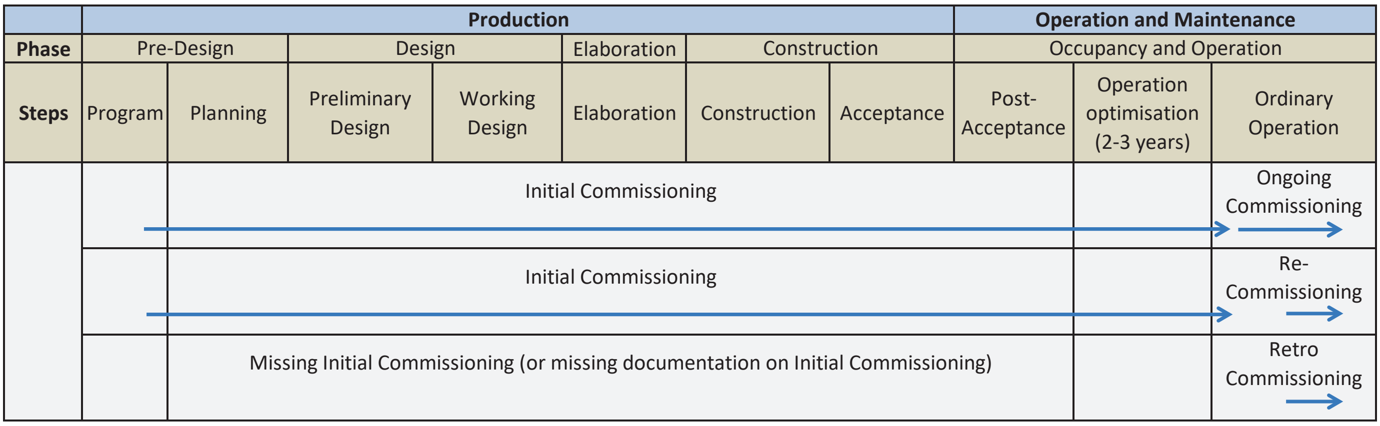
However, what can we imagine under these definitions in practice? In general, the commissioning of buildings is very broadly concerned with the energy-efficient, faultless and sustainable operation of buildings and their technical systems from the early design stage to full operation. Its methods and tools are primarily intended to ensure that advanced building components and systems efficiently work as a whole energy-wise and reach their technical potential. In the building operation phase, these are primarily tools for fault detection and diagnosis and optimisation. The design phase of the building is then generally associated with a large number of possible variants of a building's construction and HVAC system configuration. The Cx instruments in this case should assist in the assessment of the different design alternatives. Documentation of the investor requirements, the target values (e.g., energy consumption) and other important decisions and knowledge gained during the design stage of the building is also very important. The loss of information due to the lack of interconnection of the individual phases such as the design, construction, operation or change of use or owner, together with the incomplete or outdated documentation, is one of the main obstacles to the subsequent commissioning in existing buildings and a frequent cause of considerable operation issues associated with energy overconsumption. Cx tools should, therefore, also help manage information throughout the building's life cycle.

In the European Union, two large-scale projects under the Energy Conservation in Buildings and Community Systems (ECBCS) programme under the International Energy Agency (IAE) have dealt with building commissioning. These were Annex 40 (2000 – 2005) and Annex 47 (2005 – 2009) programmes, in which a number of foreign countries, universities and organisations, including the Czech Republic, participated. This research was prompted by previous projects, which came to the conclusion that most buildings do not work and never worked correctly [10]. Another impulse was the findings that by re-commissioning an HVAC system, it is possible to reach 20 – 30 % of energy savings [5]. Mills [4], who conducted research in the US under the Lawrence Berkeley National Laboratory even presents commissioning as today's most cost-effective strategy to reduce energy consumption, costs, and greenhouse gas emissions in buildings. This claim is based on a very extensive research study which analysed, in detail, the commissioning of buildings, based on a database of 643 buildings. This extensive analysis revealed that one-third of the projects for which the data were available contained more than 10 000 energy problems. The correction of these problems led to a median overall energy savings of 16 % and a commissioning payback period of 1.1 years.

In practise, four types of commissioning can be distinguished. This is an initial-commissioning, which starts during the project phase and continues through the construction to the operation of the fully occupied building. [11] The aim is to ensure that the building "behaves" as expected. Retro-commissioning is a Cx that is applied to an existing building that was never applied to that building before. Its aim is to improve the operation of the building primarily by changing the operation parameters, such as the schedule of the operation of air handling units, the application of setback regimes, optimisation of the ventilation (a necessary amount of fresh air), or by fault detection and diagnostics. Re-commissioning is a Cx type where a building that has historically gone through the Cx process will undergo another Cx process to verify or improve the building's operation. An ongoing-commissioning (also known as continuous Cx) is a Cx process performed on an ongoing basis to maintain, improve and optimise the initial commissioning of a building's systems. This continuous Cx, which is based on the continuous monitoring and a data analysis, is essential for the sustainability of energy savings, the service life of the installed technology and other savings resulting from the continuous optimisation of the operations. Thus, commissioning is not just putting the building into operation, but a holistic process that should ideally accompany the entire building process from defining the investor's requirements, through the design stage and the construction stage to the full operation of the building. An overview of the overall Cx processes and the individual types is shown in Fig. 2.

The aim of these research programmes was to enable the effective development of a common understanding of Cx, as well as to develop, validate and document commissioning tools and to initiate further research to improve the operational energy performance of buildings with a focus on HVAC systems and the related control systems. Great attention has been paid to commissioning of advanced HVAC systems, which are essential for modern low-energy buildings in order to achieve minimum or near to zero primary energy consumption and CO2 emissions. One of the main motivations for the development of the commissioning in this area is the move from the intuitive approach that is currently used in most cases of building operations to a more systematic approach aimed at achieving substantial energy savings.

Specifically, a number of methodological instructions or tools have been developed on the issue of monitoring and the use of sensors, visualisation and the analysis of measured data or tools for the detection and diagnosis of faults. Great attention was paid to the work with the data. In the case of advanced air-conditioning systems, it is necessary to process extreme amounts of data for the needs of Cx and, without the use of computer technologies, it is not possible to process such an amount of data and obtain the necessary information out of them. Within the project outputs, several tools for the data processing and visualisation, optimisation and fault detection were introduced to facilitate the identification and realisation of potential energy savings. The appropriate visualisation of the data proved to be absolutely essential for revealing



	Production							**Operation and Maintenance**		
Phase	Pre-Design		Design		Elaboration	Construction		Occupancy and Operation		
Steps	Program	Planning	Preliminary Design	Working Design	Elaboration	Construction	Acceptance	Post-Acceptance	Operation optimisation (2-3 years)	Ordinary Operation
		Initial Commissioning								Ongoing Commissioning
		Initial Commissioning								Re-Commissioning
		Missing Initial Commissioning (or missing documentation on Initial Commissioning)								Retro Commissioning

Fig. 2 The commissioning process (modified according to [8])

hidden information about the system's operation. On the other hand, the lack of analytical tools in the operation of a building often leads to overly conservative decisions on the choice of the set-points or the schedule of the operation of the individual equipment. Common examples of such conservative decisions are over-ventilation, the unnecessary operation of technical systems outside the operating hours of a building, or unnecessarily high temperature settings in the winter and too low ones in the summer.

One of the main barriers for the spreading of Cx in the market is, according to the research project results, the lack of commissioning methods and tools (especially automatic) and technologies needed for the energy efficient operation and reaching the potential of advanced components and systems of modern buildings. Further research in this field is, thus, absolutely necessary. This is especially true for advanced and extensive systems of modern and low-energy buildings. The dynamics and interactions of the individual subsystems of these complicated HVAC systems require special effort and special tools for the Cx process. Especially in these cases, increasing the efficiency of a single subsystem does not always mean an improvement within the whole system.

The main functions, for which the existence of specialised tools would make commissioning work more efficient, were listed:
- ☐ Assessment of a system's operation under the given operation conditions, including consideration of the weather conditions to assess whether the system has met the design requirements
- ☐ Fault detection and diagnostics
- ☐ Optimisation of the HVAC systems using computer simulation tools

Annex 47 also mapped the status of building Cx in the countries involved in the project. In the case of Europe, the commissioning process outside the UK was more or less new. However, the Cx process and particularly its objectives largely correspond to the EPBD objectives set by the European Commission. As a result, many national research programmes have introduced commissioning tools as a means of achieving the requirements of the Directive (EPBD). The use of Cx and its tools to achieve the objectives of the Directive is likely to have a great impact in the future, especially in view of the new EPBD 2018, which is already more concerned with the real operation of buildings.

In most European countries, however, Cx tasks are still focused only on the handover phase of the building, which, in many cases, means only a rough check of the completeness of the installation and verification of the principle functionality of the systems. This often chaotic and underestimated final phase of the building construction, together with the absence of the subsequent optimisation of its operation, leads to excessive and unnecessary energy consumption or to the reduced quality of the indoor environment. Unfortunately, the Czech Republic is no exception.

CONCLUSION

Given the high share of the total primary consumption by the building stock and the increasing demand for high-quality indoor environments, there is increasing pressure to optimise the operation of HVAC systems. The recently published European Union Directive on the Energy Performance of Buildings (EPBD 2018) also puts pressure on reducing the consumption of buildings in their actual operation and on the quality of the indoor environment [2].

In the case of environmental engineering, optimal operation is generally meant to ensure the requirements for the indoor environment quality with the minimum energy consumption. The advanced technologies and HVAC systems components used in large and modern, low-energy buildings have considerable potential for energy-efficient operations, but these technologies constantly increase the complexity of the installed systems and the impact of the interactions of the individual subsystems.

However, according to the available studies (e.g., [4], [12]), buildings usually do not operate as intended and their energy consumption is often higher than expected at the design stage of the building. To overcome this problem for non-residential buildings, a commissioning process has been introduced in recent years. By applying this process, significant energy savings can be reached and its tools and procedures help to ensure that buildings are operated correctly, energy efficiently and as required by the investor. A number of commissioning tools and technologies are needed to achieve energy-efficient operations and reach the potential of the advanced components and systems. However, further research is absolutely necessary for their development, for understanding their value and potential when applied to real projects and for achieving a nearly zero-energy building concept [13], [8].

In order for the Commissioning process to be used more widely, the whole process needs to be better standardised and practically applicable tools needs to be developed. However, at least understanding this concept and its significance and understanding the construction of the building and its subsequent operation and optimisation as a necessarily consecutive process, can mean a significant shift towards improving the real energy performance of buildings, while increasing the service life of the technical systems and the quality of the indoor environment.

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References

[1] SHAIKH, P. et al. A review on optimized control systems for building energy and comfort management of smart sustainable buildings. *Renew. Sustain. Energy Rev.* 2014, 34, 409–429.

[2] Směrnice evropského parlamentu a rady(EU) 2018/844 ze dne 30. května 2018, kterou se mění směrnice 2010/31/EU o energetické náročnosti budov a směrnice 2012/27/EU o energetické účinnosti. 2018, 844, 75–91.

[3] KNIGHT, I. Assessing electrical energy use in HVAC systems. REHVA Journal [online]. Avilable from: http://www.rehva.eu/publications-and-resources/rehva-journal/2012/012012/assessing-electrical-energy-use-in-hvac-systems.html

[4] MILLS, E. Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States. *Energy Effic.* 2011, vol. 4, no. 2, p. 145–173.

[5] VIESER, J. C. *et al. Commissioning Tools for Improved Building Energy Performance ECBCS Annex 40 Project Summary Report.* 2010.

[6] ŠIMEK, J, LAIN, M. a HENSEN, J. L. M. Reducing Energy Consumption for Air-Conditioning by Commissioning and Optimized System Operation. *IOP Conf. Ser. Earth Environ. Sci.*, vol. 290, no. 1, p. 012088, Jun. 2019.

[7] KABELE K. Změna evropské směrnice o energetické náročnosti budov (EPBD 3). [Online]. Avilable from: https://www.tzb-info.cz/energeticka-narocnost-budov/17969-zmena-evropska-smernice-o-energeticke-narocnosti-budov-epbd-3

[8] FERRETTI, N. M., MIYATA, M. a BAUMANN O. A retrospective on the impact of Annex 40 and Annex 47 research on the international state of building commissioning. *Energy Build.* 2018, 158, 54–61.

[9] LEGRIS, CH., FERRETTI, N. M., CHOINIÉRE, D. Commissioning Overview, a Report of Cost-Effective Commissioning of Existing and Low Energy Buildings, Annex 47.

[10] VIESER, J. C., JANDON, M. Commissioning tools for improved energy performance Results of IEA ECBCS ANNEX 40.

[11] CHOINIÉRE, D., FERRETTI, N. M. Cost Effective Commissioning of Existing and Low Energy Buildings.

[12] MILLS, E., MATHEW P. Monitoring-Based Commissioning: Benchmarking Analysis of 24 UC/CSU/IOU Projects, 2009.

[13] CHOINIÉRE, D., FERRETTI, N. M. Cost Effective Commissioning of Existing and Low Energy Buildings - Project Summary Report.