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Analysis and Optimization of Thermal Comfort in Residential Buildings by means of a Weather-Controlled Air-to-Water Heat Pump

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Abstract

In the described research an investigation was performed into how thermal comfort in residential buildings could be improved by means of the smart control and optimization of weather-controlled air-to-water heat pumps, taking into account the new-generation heat pumps which can be adapted to different environmental conditions. A novel approach to the off-line optimization of weather-dependent heating curves is proposed. Outdoor temperature controlled heating is extended into the field of linearly parametrized generalized heating curves, considering additional influencing factors such as solar radiation, temperature gradients, and other near-future effects. Off-line optimization is performed in order to maximize indoor thermal comfort for each different parametrization case. The study is based on a TRNSYS simulation of a residential building which included a heat pump model, and a predicted mean vote (PMV) thermal comfort model. A simulation framework for the global optimization of generalized heating curves is developed. The results of the study showed that a considerable improvement in thermal comfort can be achieved by including (in addition to the outdoor temperature) some other factors which can affect the operation of the heat pump, solar radiation being the factor with the strongest effect.

Keywords

Heat pump, optimization, simulation, thermal comfort, weather compensation, temperature, solar radiation

1 Introduction

The wider use of heat pumps is undoubtedly an energy and cost-efficient way towards the achievement of a low carbon society, and is perfectly matched with the utilization of renewable energy sources in smart cities and on smart grids. EHPA (the European Heat Pump Association) has predicted an annual market growth rate of 11.5% until 2020, and as a result ever more intensive R&D activities can be observed in this domain. Today R&D work in the field of heat pumps for residential buildings is focused in five main directions: the quest for environmentally-friendly and energy-efficient refrigerants [1-3], improvements in the energy efficiency of vapour-compression cycles and heat transfer [4-7], the introduction of various energy sources for monovalent and bivalent operation (e.g. district heating, solar, wind, etc.) [8-14], including integration into smart grids [15-18], the introduction of alternative technologies to vapour compression [19], and finally, smart control, system integration and operation [20-23]. In the case of the last-mentioned, smart algorithms are presently being developed which are based on a number of different parameters,

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such as the weather [24], human occupancy and behaviour [25-27], system specifics including available renewable energy sources [28, 29], building dynamics and the electrical grid [30], the energy market [31], and others. By implementing advanced algorithms for the smart and predictive control of heat pumps [21, 30-34], energy efficiency [35] or operational-cost efficiency [36, 37] can be achieved, as well as improved thermal comfort [38-40] of the building's occupants.

However, in most of today's real applications, smart and on-line optimization is not yet fully available, or else the end-user would, due to the excessive complexity of the system, have to pay for additional investments. For this reason simplicity and operational-cost efficiency remain very important issues. Especially if the rather stochastic quality of installed systems (due to work by inefficient or insufficiently educated installers) is taken into account. This is why, in our investigation, we looked at the possibilities for the low-cost improvement in thermal comfort by the off-line optimization of weather-controlled heating curves. The proposed approach appears to be a promising and simple alternative to online predictive control approaches, especially since it extends the use of outdoor temperature controlled heating curves to various other important influencing factors (e.g. solar radiation).

1.1 Problem formulation

Manufacturers of weather-controlled air-to-water heat pumps offer the possibility for adjustments of the temperature of heating water to be made automatically with respect to the outdoor air temperature. However, the actual setup of parameters which is required for efficient weather-controlled operation is usually approximated according to the provided operation manuals, and long-term manual adjustment is needed in order to obtain good results. Typical examples of suggested weather-controlled heating curves based on the KRONOTERM heat pump Owner's Manual [41] are shown in Figure 1. Three examples of heating curves are defined by the set-points (S_1 , S_2 , S_3), which connect the outdoor temperature T_{out} and the heating temperature T_{heat} together by means of two linear segments.

Figure 1. Typical example of three different weather-controlled heating curves for an air-to-water heat pump [41]

Although advanced approaches toward regulation of heating curves have been proposed, such as including the seasonal performance factor [42], a number of unresolved problems are associated with the definition of weather-controlled heating curves

(e.g. how can the end-user properly and efficiently adjust the heating curve), so that in this paper we have explored the following two questions which define our problem formulation:

1. What is the optimal heating curve for weather-controlled heating?
2. Are there additional weather related effects which could be included in order to improve the efficiency of weather-controlled heating?

1.2 Solution approach

Our solution approach to the proposed problem formulation included TRNSYS simulation and Matlab based analysis, and the optimization of various heating scenarios. The possibilities for the improvement of thermal comfort in buildings by means of smart control and off-line optimization of the operation of the heat pump were explored. We extended the outdoor temperature dependent heating curves into generalized heating curves which take into account, in addition to the outdoor temperature, also other influencing factors, such as solar radiation, outdoor temperature gradients, and near-future effects. We also implemented linear parametrizations of generalized heating curves, and performed their optimization in order to derive optimal heating temperatures as the output of the heat pump system. The off-line optimization of generalized heating curves results in static solutions (heating curves) therefore the indoor temperature can not be included as an additional influencing factor in the optimization procedure. The results of the study show which weather-related influencing factors should be included in the heat pump's control system in order to optimize heating performance with respect to indoor thermal comfort.

The paper is composed as follows: Section 2 introduces the construction of the TRNSYS (Transient Systems Simulation) model of the selected building, the heat pump, and the thermal comfort model. Weather data for the simulation and analysis of the building's thermal delay responses are presented in Section 3. Section 4 describes the selected parametrization and optimization approach, which includes a formulation of the optimization problem, a generalized parametrization of heating curves, and an outline of the proposed optimization procedure. Section 5 presents the simulation results and summarizes various aspects and comparisons of the obtained results. Finally, the conclusions are summarized in Section 6, with suggestions for future research.

2 Numerical model of the investigated building with its heating system

In our research we used the numerical simulation tool TRNSYS [43] in order to evaluate the effect of heat pump optimization on a building's indoor thermal comfort. A two storeys single-family building with plan dimensions of 8.0 x 11.0 m and double-pitched roof with a N-S orientation was considered as a reference building. The building with two zones was constructed in the Multi_zone building model (Type 56b). Other important technical and thermal properties of the investigated building are indicated in Table 1.

Description	Unit	Value
Living area	[m ²]	180
$U_{\text{exterior wall}}$	[W/m ² K]	0.328
U_{roof}	[W/m ² K]	0.126
U_{floor}	[W/m ² K]	0.167
$U_{\text{inner wall}}$	[W/m ² K]	2.759
U_{glazing}	[W/m ² K]	1.3
g_{glazing}	[/]	0.551
Shading factor (Sf)	[/]	0.75 if $T_{\text{in}} > 24^{\circ}\text{C}$
Infiltration	[h ⁻¹]	0.2
Ventilation	[h ⁻¹]	0.5

Table 1. Technical and thermal properties of the investigated building

In general, the use of a heat pump in a heating system is reasonable when the temperatures of the heat transfer fluid are low. For this reason, we took into account a floor heating system. The pipe system of the heating system has two loops: primary and secondary loop. Primary loop connected the heat pump and the pipe distributor in each zone, where we assumed five loops pipe (secondary loop) which is placed in concrete layer. The estimated time constant of the floor heating system is 12 h. In the primary loop we assumed the temperature regulation which is carried out by the heat pump itself, therefore we did not take into account any additional thermostatic valves or a heat buffer storage. In the secondary loop, the on/off regulation implemented by the ON/OFF differential controller model (Type 2b) was considered.

The performance of the heat pump, as well as its output thermal power and COP (coefficient of performance - the ratio between the heating power and the electrical power of the heat pump) were modelled as a function of the heating temperature (i.e. water outlet temperature) and the outdoor temperature (i.e. heat source temperature), as shown in Figure 2. In order to determine the values of the output thermal power and COP at an arbitrary point of operation, two dimensional data interpolation was applied by using the multi-dimensional data interpolation model with two independent variables (Type 581C).

Figure 2: Performance of the selected heat pump: with respect to the output thermal power (left) and the COP (right) [42]

The indoor thermal comfort which is integrated in the Multi_zone building model (Type 56b) was analysed by using the *PMV* indicator which was developed by Fanger [45]. *PMV* is a representative of a large population's perception of a thermal

environment, and is used to assess thermal comfort in standards such as ISO 7730 [46]. The basic parameters included in the indoor thermal comfort model are: air temperature, mean radiant temperature, air speed, relative humidity, clothing insulation (factor), and metabolic rate. The air temperature, the mean radiant temperature and the relative humidity were calculated by TRNSYS in hourly time steps, whereas the other parameters were assumed to be constant during the simulation. Some of the environment conditions (outdoor temperature, solar radiation and relative humidity) were read from the meteorological database (Type 9a), while the remaining environment variables were modelled by several other TRNSYS components: the incoming solar radiation on different oriented surfaces (walls, windows, roof) by the solar radiation processor model (Type 16c), the sky temperature by the effective sky temperature for long-wave radiation exchanger model (Type 69b) and the thermodynamic properties of air by the psychometrics model (Type 33e).

The numerical model of the building and the heating system were verified by comparing the results for the simulated and the measured thermal response of the building and the floor heating system. Temperature and solar radiation measurements were performed over a two-week period in February 2017. The ambient temperature was measured at the house's location, whereas data about solar radiation were obtained from the nearest weather recording station, which was approximately 13 km distant from the location of the building. A bias of $\Delta T_{in} = 0.35^\circ\text{C}$ was removed from the modelled indoor temperatures as a post-processing step. Figure 3 shows the relationship between the measured temperature and the numerically defined heating temperature T_{heat} (upper plot) and the indoor air temperature T_{in} (lower plot). The scatter plots on the right hand side show the correlation between the measured and modelled values, which can be expressed by means of the correlation coefficient $R = 0.996$ in the case of T_{heat} , and the correlation coefficient $R = 0.937$ in the case of T_{in} . It can be concluded from the results of the comparison that the numerical model was successfully verified, and therefore suitable for the simulation study presented in this paper.

Figure 3. Experimental verification of the numerical model for the investigated residential building:

heating temperature T_{heat} (upper plot), and indoor air temperature T_{in} (lower plot)

3.1 Weather data for the simulation

The simulations performed in this paper were based on weather data which were recorded in Ljubljana, Slovenia, during one typical winter season (6 months) [47]. These data include hourly measurements of the outdoor temperature T_{out} and the solar radiation SR for a period of six months, as shown in the upper plot of Figure 4. The lower plot of Figure 4 shows the details for the first three weeks.

Figure 4. Weather data recorded at Ljubljana, Slovenia, showing the outdoor temperature T_{out} and solar radiation SR for six months of a winter period, and for the first three weeks of this period

3.2 Thermal response of the building

The thermal response of the investigated building in terms of delays in changes to indoor temperature with respect to changing weather conditions is important for the estimation of the typical response times, and therefore also of the time constants which are related to the parametrization of the heat pump generalized heating curves. In order to obtain satisfactory estimates of the thermal response of the building, a cross-correlation analysis was performed between the outdoor temperature T_{out} , the solar radiation SR , and the indoor temperature T_{in} .

As the initial step, the constructed TRNSYS model was applied with a constant heating temperature of $T_{heat} = 33$ °C, which represents the temperature of the water exiting the heat pump system and entering the floor heating system of the building. This temperature was kept constant for the cross-correlation analysis in order to eliminate the influence of the building heating system. The results of the TRNSYS simulation consisted of the thermal comfort and indoor temperature measurements. The indoor temperature T_{in} was used in the cross-correlation analysis.

As the next pre-processing step, all the analysed values (T_{out} , SR , T_{in}) were normalized to a zero mean and a standard deviation one. The seasonal components were then eliminated from the temperature vectors (this is not necessary in the case of solar

radiation) by applying a high-pass filter, as shown in Figure 5. A one-week window of the prepared normalized and filtered signals is shown in Figure 6. These data were used as the input for the cross-correlation analysis.

Figure 5. The normalized and high-pass filtered temperatures (T_{out} , T_{in})

Figure 6. The normalized and high-pass filtered signals (T_{out} , SR , T_{in}) for the cross-correlation analysis

The results of the cross-correlation analysis show the following delays between the considered variables:

$$D(SR, T_{out}) = 3 \text{ hours,}$$

$$D(SR, T_{in}) = 4 \text{ hours,}$$

$$D(T_{out}, T_{in}) = 1 \text{ hour,}$$

which means that the outdoor temperature variations follow the solar radiation variations with a delay of 3 hours, the indoor temperature variations follow the solar radiation variations with a delay of 4 hours, and the indoor temperature response is related to the outdoor temperature with a delay of 1 hour. These results are very important for preliminary estimates of the effects which need to be taken into account in generalized heating curves. They indicate that the building response times are within a time horizon of a few hours. The presented time delays are valid for the specific case study applied in our research which represents a typical residential building. Although similar results can be obtained for many residential buildings, it can be expected that these findings will change for different types of buildings (with different types of skins, windows, ventilation, etc.). But the most important finding is independent from the considered building, namely the 3 hours delay between outdoor temperature and solar

radiation means that solar radiation measurements include the information that outdoor temperature measurements will reveal only 3 hours later. This finding has a strong significance for including solar radiation into the parametrization of heating curves, as discussed in the next section.

4 Parametrization and optimization approach

4.1 Formulation of the objective function and the constraints

The objective of the proposed solution approach to the optimization of heating curves is to find an optimal operation of the heat pump with respect to maintaining as small as possible deviation from the desired thermal comfort in the building. A standard heat pump installation with continuous operation was considered. For this type of heat pump installation, the available control mechanism is regulation of the heating temperature T_{heat} , which represents the temperature of the water exiting the heat pump system and entering the building's floor heating system.

In this study, we defined the optimization goal as minimization of the deviation from the desired thermal comfort level (expressed by PMV) while maintaining positive PMV values. According to the definition of PMV , the target PMV value denoting optimal comfort is defined by $PMV = 0$, and the deviations in our case study were defined as the root mean square deviation from the target PMV , so our objective function J can be expressed as:

$$J = \sqrt{\frac{\sum_{t=1}^N PMV(t)^2}{N}} \quad (1)$$

where t denotes the time steps with an hourly resolution, and N is the total number of time steps. In the case of our simulation, which covered one winter season (i.e. to a period of six months), the number of time steps amounted to $N = 4368$.

In our simulation study we also took into account two different optimization constraints. The first constraint was that the PMV values should never be allowed to be negative (i.e. the residents should never feel any negative thermal discomfort):

$$\forall t: PMV(t) \geq 0 \quad (2)$$

whereas the second restraint was that the heating temperature T_{heat} should not drop below 20 °C as this would imply cooling and not heating (such a situation was not considered in this study):

$$\forall t: T_{\text{heat}}(t) \geq 20 \text{ } ^\circ\text{C} \quad (3)$$

The defined objective function given in Eq. (1) and the optimization constraints given in Eqs. (2-3) provide a formal expression of our optimization objective.

4.2 Generalized parametrization of heating curves

As one of the main contributions of this study, we propose a novel generalized function of the heating temperature T_{heat} , depending on the various external weather-related parameters, such as the outdoor temperature T_{out} and the solar radiation SR . With such a formulation it was possible to express both the standard heating curve specification (Figure 1), and also novel generalized heating curves. In a generalized parametrization, the heating temperature T_{heat} is expressed as a function of the current and future weather related parameters and optionally also of other influencing factors, as follows:

$$T_{\text{heat}}(t) = f(T_{\text{out}}(t), SR(t), \dots, T_{\text{out}}(t+h), SR(t+h), \dots) \quad (4)$$

where h denotes a time horizon expressed in hours, and f is an arbitrary linear or nonlinear function. In our study, the function f was approximated by a linear regression in order to simplify the simulation, and also because the results of preliminary simulations showed that a nonlinear function is not necessary for this type of heating curve parametrization. In this case, generalized heating curve parametrization (4) is reduced to the linear expression which was applied in our simulation study:

$$T_{\text{heat}}(t) = p_0 + p_1 T_{\text{out}}(t) + p_2 SR(t) \dots + p_3 T_{\text{out}}(t+h) + p_4 SR(t+h) \dots \quad (5)$$

Various linear parametrizations were explored with the aim of finding the most influential factors which need to be taken into account when optimizing thermal comfort. The following functions $F = \{F_1, F_2, F_3, F_4, F_5, F_6\}$ were considered:

$$F_1: T_{\text{heat}}(t) = p_0 \quad (6)$$

$$F_2: T_{\text{heat}}(t) = p_0 + p_1 T_{\text{out}}(t) \quad (7)$$

$$F_3: T_{\text{heat}}(t) = p_0 + p_1 T_{\text{out}}(t) + p_2 \Delta T_{\text{out}}(t) \quad (8)$$

$$F_4: T_{\text{heat}}(t) = p_0 + p_1 T_{\text{out}}(t) + p_2 SR(t) \quad (9)$$

$$F_5: T_{\text{heat}}(t) = p_0 + p_1 T_{\text{out}}(t) + p_2 SR(t) + p_3 T_{\text{out}}(t+3) + p_4 SR(t+3) \quad (10)$$

$$F_6: T_{\text{heat}}(t) = p_0 + p_1 T_{\text{out}}(t) + p_2 SR(t) + p_3 T_{\text{out}}(t+3) + p_4 SR(t+3) + p_5 T_{\text{out}}(t+6) + p_6 SR(t+6) \quad (11)$$

The function F_1 defines a constant heating temperature and is applied for comparative purposes only. The function F_2 describes a standard weather-controlled heating curve which includes dependence on the outdoor temperature T_{out} . The functions F_3, F_4, F_5 and F_6 are novel contributions of this paper, and represent extensions of the weather compensated control by including the outdoor temperature gradient, solar radiation, and near-future effects. In Eq. (10) a near-future horizon of $h = 3$ hours was selected, based on the results of a cross-correlation analysis of the thermal response of the building, which showed that the response times were

within a time horizon of a few hours. An additional time horizon of $h = 6$ hours was added in the case of the last-considered function, i.e. F_6 , in order to explore possible delayed effects. Further horizons were also explored but it was found that they did not make any significant contribution to improvement of the results. Similar horizons (such as $h = 2$ hours) also provided similar and not significantly different results, so that it was not necessary to take into account explicitly all possible near-future effects.

4.3 Formulation of the optimization problem

Based on a formulation of the objective function, the constraints, and the parametrization of possible solutions, it was possible to define the optimization problem as follows:

$$\min_{\{p_0, p_1, p_2, \dots\}} \sqrt{\frac{\sum_{t=1}^N PMV(t)^2}{N}}, \quad \forall t: PMV(t) \geq 0, \quad \forall t: T_{heat}(t) \geq 20^\circ C \quad (12)$$

The optimization objective was to find an optimal parameter vector $p = \{p_0, p_1, p_2, \dots\}$ for each parametrization case as defined in Eqs. (6-11) which minimizes the objective function given in Eq. (1) and satisfies the optimization constraints given in Eqs. (2-3).

4.4 Framework of the optimization procedure

The optimization procedure is designed to find solutions to the optimization problem (12) for various parametrization cases as defined by the functions given in Section 4.2. The framework of the optimization procedure can be formulated by the following steps:

1. Select a function F_i ; $i=1,2,\dots,6$ that defines the parametrization $T_{heat}(p_0, p_1, p_2, \dots)$ according to Eqs. (6-11).
2. Prepare the required weather-related data ($T_{out}(t), SR(t), \dots$) for a selected period $t = 1, \dots, N$ ($N = 4368$ for 6 months, from October till March).
3. Start an optimization loop:
 - i. Generate a new parameter vector $p = \{p_0, p_1, p_2, \dots\}$.
 - ii. Generate a vector of the heating temperatures $T_{heat}(t)$, $t = 1, \dots, N$, according to the parameter vector p and the selected function F_i .
 - iii. Run a TRNSYS simulation with the selected weather data and the generated heating temperatures.
 - iv. Calculate the PMV and the objective function J .
 - v. Continue optimization until the termination criterion is met.
4. End the optimization loop
 - i. Save the most successful parameter vector p which minimizes the optimization problem presented in Eq. (12) for each function F_i ; $i=1,2,\dots,6$.

In spite of the recent popularity of many nature-inspired optimization approaches [48], such as genetic algorithms [49], particle swarm optimization [50], ant colony optimization [51] and others, in our case a heuristic global search algorithm [52] was applied due to its simplicity, efficiency, and robustness of operation. The complete optimization framework was implemented in Matlab. The proposed solution approach thus combines Matlab based numerical optimization, and TRNSYS based simulation models of the selected building, the air-to-water heat pump, and thermal comfort. As a termination criterion, the maximum number of trial points (from which to begin the optimization) was set to 1000. After completing the optimization simulations for all the functions defined by Eqs. (6-11), the results were summarized and evaluated, as is described in the next section.

5 Simulation results

This section summarizes the simulation results which were obtained by performing the optimization procedure described in previous section. The best results, i.e. those which were the best with respect to the formulation of the optimization problem (12), are presented for each function F_i ; $i=1,2,\dots,6$.

5.1 The F_1 case: constant heating

The first result is shown in Figure 7 for the function F_1 which describes a constant heating temperature. In this case, the minimum value of the objective function $J = 0.558$ was obtained while maintaining a constant heating temperature of $T_{\text{heat}} = 32.5^\circ\text{C}$. This solution does not provide satisfactory thermal comfort in the building, which means that its occupants would probably often open windows in warmer periods in order to compensate for excessive heating.

Figure 7. The results for the function F_1

5.2 The F_2 case: standard outdoor temperature-controlled heating

The next result, which is shown in Figure 8, corresponds to a standard outdoor temperature controlled heat pump operation, denoted by the function F_2 . In comparison with the constant heating temperature in case of F_1 , a considerable improvement in thermal comfort is achieved, which is in this case due to the regulated heating $T_{\text{heat}}(t)$ so that a minimum value of the objective

function $J = 0.168$ can be achieved. This solution already provides satisfactory thermal comfort in the building, although it should be noted that this is the optimal result that can be achieved at this level of parametrization. In practice it would be very difficult to achieve this result by incremental manual tuning of the heating curve.

Figure 8. The results for the function F_2

5.3 The F_3 case: including the temperature gradient

The function F_3 represents an attempt to exploit also the available outdoor temperature gradient ΔT_{out} which can be estimated by the temperature difference during the previous hour:

$$\Delta T_{out}(t) = T_{out}(t) - T_{out}(t - 1). \quad (13)$$

In this case, a minimum value of the objective function $J = 0.156$ can be achieved, which represents only a very small improvement compared to the F_2 case. The result is shown in Figure 9, from which it can be concluded that the available temperature gradient estimation (without using near-future information) does not provide a significant contribution to the weather control of the heat pump operation.

Figure 9. The results for the function F_3

5.4 The F_4 case: including solar radiation

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A considerable improvement can be achieved by applying the function F_4 , which takes into consideration the effect of solar radiation $SR(t)$. In this case, a minimum value of the objective function $J = 0.102$ can be achieved, as is shown in Figure 10. Large fluctuations in the heating temperature $T_{\text{heat}}(t)$ can be observed which compensate for the effect of solar radiation, and thus improve the stability of the thermal comfort in the building. Use of this formulation results in a significant improvement beyond those provided by solutions which depend only on the outdoor temperature. This improvement is due to the strong direct effect of solar radiation on the thermal balance of the building, and it is also supported by the thermal response delay (as discussed in Section 3.2), where the information about solar radiation relates to the thermal effects that will impact the building within the next few hours.

Figure 10. The results for the function F_4

5.5 The F_5 case: including near-future effects

The function F_5 includes, as influencing factors, also the near-future outdoor temperature $T_{\text{out}}(t + 3)$ and the near-future solar radiation $SR(t + 3)$. Exact values of near-future outdoor temperature and near-future solar radiation were used, and not values based on weather forecasts, therefore the results can be considered only as hypothetical and too optimistic. In this case, a minimal value of the objective function $J = 0.089$ is obtained, which confirms the beneficial impact of the inclusion of future effects, although this improvement is not very large compared to the function F_4 . The results are shown in Figure 11. The problem with this formulation is that exact values of near-future effects are not available, so that near-future weather forecasts need to be obtained, which would partially reduce the benefit due to the implicit inaccuracy of weather forecasts. For this reason, in a realistic situation only a very small improvement can be expected.

Figure 11. The results for the function F_5

5.6 The F_6 case: extending the near-future effects

The last function F_6 extends the near-future effects to $T_{out}(t + 6)$ and $SR(t + 6)$. Also in this case, the exact values of near-future outdoor temperature and near-future solar radiation were used, and not values based on weather forecasts. In this case, a minimum value of the objective function $J = 0.083$ is obtained, which indicates that including additional near-future weather effects does not result in a significant improvement in indoor thermal comfort. This is even more evident in a realistic situation (as discussed in Section 5.5), where exact values of near-future effects are not available and have to be estimated based on available weather forecasts. The results are shown in Figure 12.

Figure 12. The results for the function F_6

5.7 Comparison of the results and discussion

A comparison of results is summarized in Figure 13, which shows the values of the objective function J for all the investigated functions (shown in the upper plot), and also the required electrical power consumption Q_{elec} applied in each case (shown in the lower plot). The F_1 case is a benchmark with a constant heating temperature, whereas the cases F_2 and F_3 , provide the best results for outdoor temperature controlled regulation, and the cases F_4 , F_5 , and F_6 include solar radiation and near-future effects.

Compared to the benchmark case F_1 , a significant drop in the obtained values of the objective function J can be observed in all the subsequent cases, whereas only minor differences can be observed in electrical power consumption Q_{elec} .

Figure 13. The summarized results: values of the objective function J and of the applied electrical power consumption Q_{elec} for all the investigated functions $\{F_1, F_2, F_3, F_4, F_5, F_6\}$

In terms of thermal comfort, outdoor temperature controlled heating (F_2) provides a large improvement over the constant heating case (F_1), whereas adding temperature gradients (F_3) does not significantly improve the thermal comfort. The next improvement can be made by including the solar radiation input in the weather-controlled heating (F_4), which significantly improves the indoor thermal comfort (resulting in a 36% drop in the value of the objective function, compared to the F_3 case). This solution doesn't rely on future inputs, so it can be easily implemented by adding a solar radiation sensor to the heating system. The last two solutions, i.e. F_5 and F_6 , explore the possibility of including near-future weather related effects, from which it can be seen that the contribution of these effects to the improvement of thermal comfort is not very significant, and that their implementation would require reliable near-future weather forecasts (including solar radiation forecasts). For this reason these solutions are less suitable for practical implementation.

In terms of electrical power requirements, it is interesting to note that all of the investigated solutions show a similar magnitude of electrical consumption, which is due to the fact that all the presented solutions are optimized, and represent the best available solution within the given parametrization approach. However, a gradual reduction in the consumption of electricity can be observed for all the subsequent parametrizations, which confirms the validity of the hypothesis that improving thermal comfort by reducing excessive heating also simultaneously contributes towards electrical energy savings.

An interesting comparison between the heating temperatures T_{heat} and the outdoor temperatures T_{out} can be observed when the graphs are plotted for all the functions $\{F_1, F_2, F_3, F_4, F_5, F_6\}$ in Figure 14. Whereas the first two functions F_1 and F_2 maintain a

static dependence of the heating temperature T_{heat} on the outdoor temperature T_{out} , the other functions ($F_3, \dots, F_6$) show a very dynamic response to the outdoor temperature due to the inclusion of the additional influencing factors. Figure 14 therefore provides a good graphical illustration of the extension of the standard outdoor temperature controlled heating curve (F_2) into various types of generalized heating curves (F_3, F_4, F_5, F_6).

Figure 14. Comparison of heating temperatures and outdoor temperature for all of the analysed functions $\{F_1, F_2, F_3, F_4, F_5, F_6\}$

A comparison of a standard heating curve (F_2) and a generalized heating curve (F_4), in practical terms, is shown in Figure 15, comparing heating temperatures for the F_2 case and the F_4 case. Whereas the first case (F_2) only takes into account the effect of the outside temperature, the second case (F_4) also takes into account the effect of solar radiation. For this reason a very dynamic response can be observed in the F_4 case, lowering the heating temperature rapidly when the heating is not required due to the effect of solar radiation.

Figure 15. Comparison of the heating temperatures for the two functions F_2 and F_4

The results of this study confirmed that by taking into account effects such as that of solar radiation, the area below the static heating curves can be exploited, with the lowering of the heating temperature T_{heat} whenever possible, thus increasing the indoor thermal comfort. The presented results clearly indicate the possibility of improving thermal comfort in buildings by implementing the smart regulation of their heat pumps by adding a solar radiation input to the heat pump regulation system.

6 Conclusions

In this paper a novel approach to the off-line optimization of air-to-water heat pumps in residential buildings was investigated. The aim of the proposed method was to optimize indoor thermal comfort by the smart regulation of the heating temperature of the heating system with respect to the external environmental conditions. The proposed method extends standard outdoor temperature controlled heating curves into generalized heating curves by considering additional effects, such as solar radiation, and near-future effects. Various linearly parametrized functions are proposed and investigated with respect to their ability to positively contribute towards optimized thermal comfort in buildings.

The results of the investigation confirmed the hypothesis that the inclusion of the instantaneous value of solar radiation significantly improves thermal comfort, if properly included and optimized into a parametrized solution for regulation of the heat pump. The taking into account of near-future influences, such as those of outdoor temperature and solar radiation within a time horizon of several hours, also results in a positive contribution towards the improvement of thermal comfort, although the taking into account of near-future effects implies access to reliable weather forecasts, which limits the applicability of this approach. Because of this, based on the results of this study we can recommend the utilization of solar radiation input as an additional factor in the case of weather-controlled air-to-water heat pumps installed in residential buildings.

The proposed approach can be used to obtain optimized heating curves without the need for manual tuning, which is usually done either by the end user, or by an authorized technician. The advantage of this method in comparison with other model predictive control approaches is that it doesn't require online calculations of daily heating regimes, but calculates in an off-line simulation

the optimal generalized heating curves that can be applied to regulate the heating temperature of the heat pump system. The results of this study are generic with respect to evaluation of contributions of various terms in the generalized heating curves, however the coefficients of resulting generalized heating curves may differ for different buildings and therefore the off-line optimization should be performed on each building. In order to implement the proposed strategy in real buildings, future research will need to be focused on a wider diversity of building types, and on the development of simplified building models that can be adapted to specific buildings. Further research should be conducted in order to exploit the existing heat pump operation data of buildings in order to make the building models suitable as a basis for the proposed optimization of the heat pump operation.

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Highlights

- A new approach to the optimization of weather-controlled heat pumps is proposed
- TRNSYS models of a building, heat pump, and thermal comfort are constructed
- Outdoor temperature controlled heating is extended to generalized heating curves
- An improvement in thermal comfort can be achieved by considering additional factors
- Solar radiation is the additional factor with the strongest effect