Heat pump system control: the potential improvement based on perfect prediction of weather forecast and user occupancy

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Abstract

This paper presents an improvement potential study for residential heat pump heating systems based on predictive rule-based control strategies developed considering the perfect prediction of weather forecast and human behavior information. In particular, the study exploits the profile forecast of Domestic Hot Water (DHW) consumption, ambient temperature and solar radiation. The internal gain contribution due to the user occupancy and activity is also considered adopting a stochastic occupancy profile. The study has been performed by means of TRNSYS numerical simulations and a model of a Ground Source Heat Pump system is here described. The developed model considers a typical single family house including a heat pump unit, an auxiliary heater and a stratified storage tank. A basic degree-minute on-off controller has been adopted as a benchmark. Considering the DHW consumption over the summer season, the improved control logic yields a potential enhancement of indoor temperature stability. With reference to the Swedish heating season, the highest potential in terms of reduction of energy consumption is given by the exploitation of instantaneous and forecasted solar radiation.

Keywords: Heat Pump system control; HVAC predictive rule-based control; weather forecast; occupancy behavior; internal gain; ambient temperature; perfect prediction.

1. Introduction

Heat pumps (HP) represent a mature and well known technology for building heating and cooling purposes. In 2014 a total amount of 1.7 million units have been sold in European Union with Sweden leading the ground source market share. A total heat pump capacity of over 6.6 GW was installed for an estimated energy production of about 13 TWh. Only in Sweden, over 1.4 million units are estimated to be in operation and the heat pump represents the most popular heating system for residential buildings, covering, together with electric heating, over 35% of the total heating demand [1, 2, 3].

According to the 2010 European Performance of Building Directive member states shall ensure that all new buildings constructed after 2020 should be "near zero energy" [4] and building heating systems are now accounting for 40% of the total energy consumption. The residential sector represents the 27% of the global energy consumption and it grew by 14% from 2000 to 2011 [5]. Hence, the current and near and far future goal of reducing

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greenhouse gas emissions involves the study of new solutions to improve the energy efficiency of heating systems in new and existing buildings.

Heat pump industry development has reached a mature state over the last 20 years and the research and development potential for further performance improvement of unit components such as compressors or heat exchangers is economically less and less sustainable for manufacturers. On the other hand, the computational power of electronic device has been increasing together with storage and connection capability. For these reasons there has been a growing interest in the possibility to introduce advanced features in the heat pump system controllers in order to improve the overall system performance by enhancing the control logic algorithms.

Hutchteman and Muller [6] show that by just adjusting the supply temperature from the heat pump based on internal gain, it is feasible to reduce the annual electricity consumption by 6.8%.

Several control approaches able to improve the system performance have been developed and a number of review studies have been proposed in order to define the state-of-art from different points of view. Fisher et Madani [7] propose a review of heat pump system definitions and control strategies from the smart grid concept perspective. Afram and Janabi-Sharifi review [8] focuses on the comparison of Model Predictive Control (MPC) approach with respect to other control implementations. Atam and Helsen [9] work contains a review of control methods dedicated to Ground-coupled Heat Pump (GCHP) systems.

MPC approach has been proposed by several authors for controlling heat pump systems including additional input compared to base on-off controller such as weather forecast and user occupancy data. In some cases, the assumptions of perfect prediction and no mismatch between the optimization model and the controlled entity has been adopted while some studies also include the input forecast uncertainties [10]. Worth noticing, the benchmark adopted for the energy saving potential is mostly a basic controller.

Oldewurtel et al. [11] performed a large-scale simulation study based on 1280 installation cases with different type of buildings, HVAC systems and weather conditions at four representative European sites. Stochastic and deterministic MPC approaches have been compared to discuss the advantage of accounting for uncertainties related to the weather forecast.

Gyalistras et al. [12] discussed the energy saving potential related to HVAC control comparing both non-predictive and predictive rule-based algorithms to MPC, including the weather and occupancy forecast. The study considered 64 different buildings at four European sites and the energy saving potential with MPC approach has been estimated to be between 16% and 40%, varying with location and building type.

Dong and Lam [13] presented the results of a test-bed experiment employing over 100 sensors measuring indoor environmental parameters, power consumption and ambient conditions. The experiments were carried out for two continuous months in the heating season and for a week in the cooling season. Local weather forecasting and occupant behavior detection have been included into an MPC design. The results showed a 30.1% measured energy reduction in the heating season compared with the conventional scheduled temperature set-points, and 17.8% energy reduction in the cooling season.

Betran and Cerpa [14] presented a MPC framework for smart building control with several components, including occupancy sensing in real-time, occupancy prediction models based on historical occupancy data, thermodynamic building models and weather forecasting data. The MPC optimization was set to minimize monetary costs in energy use while maintaining quality comfort bounds for the users. The control framework has been tested in a real office building with over 40 workers, and the calculated energy saving resulted to be around 35% and with an additional 14% savings by using occupancy detection and an occupancy prediction model.

Other works considered fuzzy-logic as an alternative to MPC [15, 16, 17] and the results of grey-box based controllers are compared to PID or basic on-off solutions.

Despite a large amount of valuable research works, implementing different types of MPC approaches, claim impressive performances related to energy saving potential, the industrial development has so far not followed this studies for HVAC system control. This is mainly due to the complexity of the control formulation and implementation. Also, the resulting control system maintenance and setting flexibility are generally not user-friendly [18]. The computational demand for solving the resulting optimization problem is typically much higher than in rule based approach [7]. MPC algorithms can be considered not ready to be massively deployed also because the current implementations require information on the state of the building that involve measurement devices not usually present in ordinary buildings [19].

A realistic alternative consists in the adoption of rule-based decision strategies where the control logic is based on expert system engineering approach. In particular, a rule based approach based on input prediction, if properly designed, represent a good compromise between MPC and non-predictive methods, being computationally inexpensive and generally more easy to be implemented.

In this paper an improvement potential study is discussed focusing on the possibility to adopt a predictive rule-based approach in order to enhance the performance of a heat pump heating system for residential buildings in terms of energy saving and indoor temperature stability. A TRNSYS model has been developed in order to simulate the dynamic behavior of the entire heating system. The simulation model is first presented and the base control logic is described. Then the developed control logics are discussed focusing on two different control objectives, one considering the maximization of the energy saving and the other aiming at the minimization of the indoor temperature deviation with reference to given upper and lower limits. A parameter named Dead-Band Deviation (DBD) is introduced in order to compare the results in terms of indoor temperature stability.

2. System modeling

A TRNSYS dynamic model has been developed considering a single family house heating system. The system layout, as shown in Fig. 1, includes the simulation sub-models of Borehole Heat Exchanger (BHE), Ground Source Heat Pump (GSHP), storage tank building, circulation pumps and auxiliary heater.

The Heat Pump considered is a ground-source single speed unit modeled by means of a performance map provided by a European manufacturer and polynomial equations for the compressor electrical power and condenser heat transfer rate has been derived as a function of the approaching heat source temperature to the evaporator (brine side) and approaching heat sink temperature to the condenser (water side), respectively named source temperature (T_{source}) and load temperature (T_{load}). The heat pump has been sized scaling the polynomial equation in order to obtain a heat capacity equal to the building heat demand (balance point) when the ambient temperature is about -4°C.

The ground heat exchanger is implemented by means of a short-term ground response model based on a borehole thermal resistance and capacitance approach.

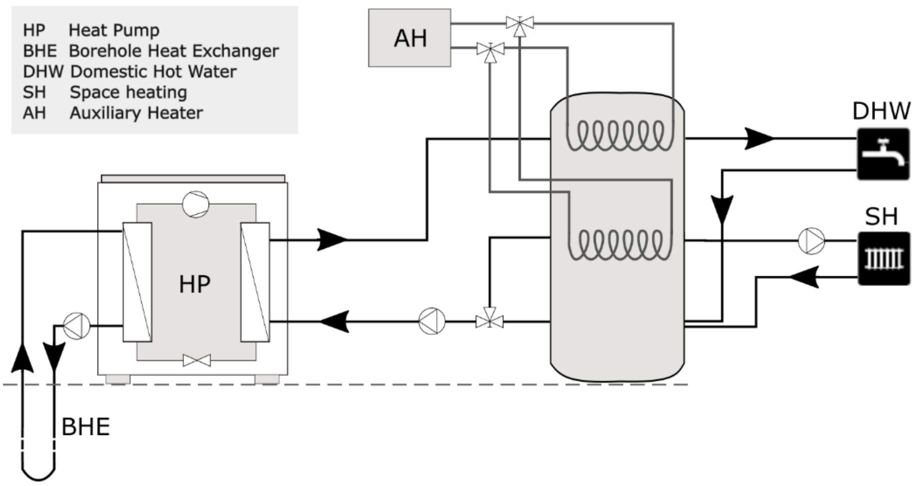

Fig. 1 Layout of the heat pump heating system considered in this study

The storage tank is connected on the heating generation side to the heat pump condenser and on the heating distribution side to the hydronic loops for both Domestic Hot Water (DHW) and Space Heating (SH). It is modeled as a 300 l stratified cylindrical tank with 10 virtual isothermal volume nodes. Both hydronic loop connections are modeled through three ports. On the heating distribution side, the virtual top node is connected to the domestic hot water, the middle node is connected to the space heating and the bottom node is connected to the return water flow. On both heat pump and heating distribution sides, the inlet node is dynamically chosen according to the inlet water temperature in order to preserve the temperature stratification.

Two coiled heat exchangers are modeled inside the storage tank, one in the virtual top node for DHW and one in the middle node for SH. Both heat exchangers are connected to an auxiliary heater operating when the heat pump is not sufficient to fulfill the DHW or space heating demand. For DHW operation mode, the auxiliary heater has a heating capacity of 5 kW while for the SH mode the auxiliary heater can operate at three different stages delivering a power of 3, 6 or 9 kW.

The building dynamic sub-model considers a single zone with reference to the characteristics and information provided by the Tabula web tool [20] for a standard Swedish residential building. A single family house located in Stockholm (Sweden) and built between year 1996 and 2000 is considered and the structure characteristics are implemented in TRNSYS consistently with this choice. The glazing surfaces represent the 33% of the wall surface and the 18% of the total envelope including the roof surface.

For the given building model characteristic, a building heating curve is defined in order to calculate the required supply temperature of the space heating distribution system. As shown in Eq. 1, for the modeled system, the required supply temperature (T^r_{supply}) is expressed as a broken line with two different slopes in the ambient temperature (T_{ambient}) ranges between -20 and -5 ˚C and between -5 and 12°C.

$$T^r_{\text{supply}} = \begin{cases} -0.85 \cdot T_{\text{ambient}} + 39.5, \text{ if } T_{\text{ambient}} < 5°\text{C} \\ -1.80 \cdot T_{\text{ambient}} + 44.2, \text{ if } T_{\text{ambient}} \geq 5°\text{C} \end{cases} \quad (1)$$

The space heating distribution system consists in radiators and it is modeled through the TRNSYS Type 362. The middle port of the thermal storage tank supplies the radiator and the return flow enters the thermal storage tank at the node with the closest temperature. A tempering valve coupled with a mixing valve is included in the system at the radiator loop return in order to keep the radiator supply temperature close to the required temperature (T^r_{supply}). A Proportional Integrative controller (PI) has also been implemented and tuned to control the mass flow rate of the radiator and maintain the supply temperature as close as possible to the set point given by the heating curve (T^r_{supply}).

Two different operating modes are defined for the heat pump system controller. In the DHW mode the on-off controller operates according to a constant hysteresis logic and it is set to maintain the storage tank top node temperature not lower than 42.5°C. The heat pump is turned on when the storage tank temperature is lower than 42.5°C and it is turned off when the tank temperature reaches the value of 47.5°C. The auxiliary heater is turned on providing a heating power of 5 kW when the storage tank temperature of the top node is lower than 42.5°C for more than 20 minutes and it is turned off when the temperature reaches the value of 45°C. In the SH mode the controller logic is based on a degree-minute parameter (DM) defined in Eq.2 [21].

$$DM = \left(T_{supply} - T^r_{supply}\right) \cdot t + DM_{old} \quad (2)$$

Where T_{supply} is the actual space heating supply temperature, T^r_{supply} is the supply temperature given by the building heating curve, *t* is the time expressed in minutes and DM_{old} is the previous degree-minute value.

According to the algorithm implemented in the system controller the heat pump is turned on when DM is lower than -60 degree-minute and it is turned off when DM reaches 0 degree-minute.

The degree-minute value is reset to zero when the difference between the actual and the required supply temperature values are greater the 10°C or the degree-minute value is higher than 300. The first, second and third stages of the auxiliary heater (3kW, 6kW, 9kW) are turned on when DM is lower than -600, -680 and -760 degree-minute respectively. The logic for turning off the space heating auxiliary heater is based on the temperature difference. The third, second, and first stages are turned off when the difference between the actual and the required supply temperatures is higher than 1K, 2K and 3K respectively.

Among the simple on-off control techniques the degree-minute control logic has been demonstrated to guarantee the lowest annual energy usage of both compressor and electric auxiliary heater and the highest seasonal performance factor compared to constant or floating hysteresis methods [21].

3. Improved control logic implementation

An improved potential study has been carried out in order to evaluate the possible enhancements of the heating system described above considering new control strategies based on additional input information. As shown in Fig. 2, auxiliary variables have been added to the system controller including the forecast of DHW consumption, internal gain, ambient temperature and solar radiation. For this study, the developed control logics described below are based on the assumption of perfect prediction for the forecasted data.

3.1. Domestic hot water consumption perfect prediction

A DHW consumption profile based on a stochastic bottom-up model [22] has been adopted and specified for a residential building with 2 adults and 2 children.

The improved logic has been developed calculating a dynamic draw-off schedule considering the forecasted DHW profile. The purpose of this approach is to develop an improved control logic based on the idea of running the system reducing the electrical energy consumption. The dynamic schedule approach considers the amount of energy required by the draw-offs and it is therefore based on dynamic anticipation of the energy request. In particular, the anticipation time is computed by the ratio between the future energy demand and the expected condenser heat rate based on an average of the condenser power. For each draw-off, the anticipation time is evaluated as the running time required by the Heat Pump to provide the related amount of energy.

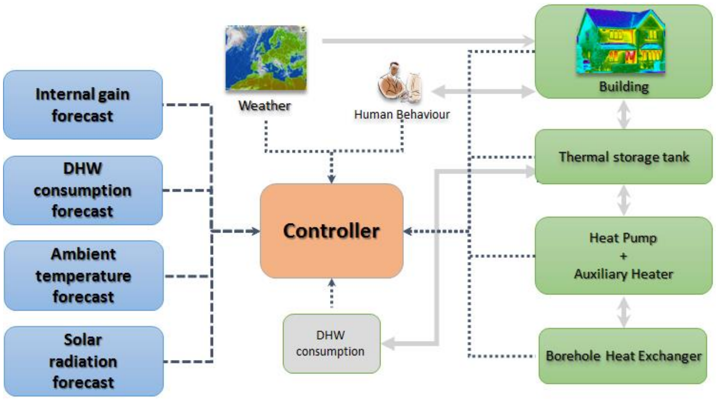

Fig. 2 Conceptual model of the modified heating system considered in this study

In the controller, the dynamic schedule signal is combined with the on-off hysteresis signal the heating system operation mode is selected depending on the thermal storage tank temperature at the virtual top node. Worth mentioning, the implemented control logic always prioritizes the DHW demand over the space heating.

3.2. Internal gain

A stochastic occupancy profile model [23] combined with metabolic rate and domestic lighting power gains have been adopted in order to calculate an internal gain profile consistent with the single family house application considered in this study.

Similarly, to the approach adopted for the DHW consumption control logic, an anticipation schedule has been calculated based on the perfect prediction of the internal gain profile forecast. The anticipation period adopted is fixed to one hour. In order to investigate the impact of the internal gain on the room temperature and the energy saving potential, the monthly solar radiation has been considered constant to the average value of each month.

The approach adopted is based on the modulation of the building heating curve by introducing a linear offset correction to the required supply temperature (T^{r}_{supply}) based on the internal gain profile. A distinction has been made in order to define different operation modes, one focusing on the thermal comfort condition stability ("comfort mode") and one focusing on the maximization of the energy saving ("economy mode").

3.3. Ambient temperature

A control logic able to adjust the building heating curve based on the perfect prediction of the ambient temperature has been developed. The idea of the developed control logic is to modulated the heating curve depending on the future condition. In this preliminary study, a shifted ambient temperature profile is considered and the modified heating curve is calculated according to a set of adjusting parameters for the entire heating season. The weather data are based on the Meteonorm database considering the typical meteorological year. Several tests have been performed in order to select the best shifting period and the anticipation period of one hour has been finally employed. If an increase in the ambient temperature is predicted, the required supply temperature has to be lowered in order to increase the degree-minute value up to zero and reduce the temperature difference with the current supply temperature. On the other hand, if the ambient temperature is predicted to decrease the required supply temperature has to be raised in order to decrease the degree-minute value.

3.4. Solar radiation

Following the same approach adopted for the development of a control logic based on the ambient temperature prediction, a procedure for the heating curve modulation based on the perfect prediction of the solar radiation profile has been implemented in the TRNSYS model in order to investigate the energy saving potential that can be achieved.

As well as for the ambient temperature case, the room temperature is influenced by the solar radiation and the aim of the developed control logic is to avoid the possible building overheating maintaining a more stable room temperature close to the set point value.

The solar radiation profile has been provided by the Meteonorm database. A set of 4 corrective coefficients have been employed to adjust the heating curve accounting for the energy gain by considering both the instantaneous and predicted total radiation.

4. Results

The control logics described in the present improvement potential study have been implemented and refined exploiting the system model developed using TRNSYS. The results are here summarized and discussed with reference to the basic on-off control logic based on the degree-minute approach described in section 2.

For all the simulations, in order to discuss the results in term of indoor temperature stability, a dedicated parameter has been defined with respect to a temperature dead-band of ±0.5°C for the room temperature. The parameter takes into account the duration and the magnitude of the deviation from the dead-band limits and can be specified for both space heating and domestic hot water modes. The discretized expressions of the temperature dead-band deviation (DBD) parameter is shown in Eq. 3 and Eq. 4.

$$\mathrm{DBD_{SH}} = \sum_{i=0}^{n} \begin{cases} (T_{\mathrm{low,\,i}}^{\mathrm{SH}} - T_{\mathrm{actual,\,i}}^{\mathrm{SH}}) \cdot (t_i - t_{i-1}), \text{ if } T_{\mathrm{actual,\,i}}^{\mathrm{SH}} < T_{\mathrm{low,\,i}}^{\mathrm{SH}} \\ (T_{\mathrm{actual,\,i}}^{\mathrm{SH}} - T_{\mathrm{high,\,i}}^{\mathrm{SH}}) \cdot (t_i - t_{i-1}), \text{ if } T_{\mathrm{actual,\,i}}^{\mathrm{SH}} > T_{\mathrm{high,\,i}}^{\mathrm{SH}} \end{cases} \tag{3}$$

$$\mathrm{DBD_{DHW}} = \sum_{i=0}^{n} (T_{\mathrm{low,\,i}}^{\mathrm{DHW}} - T_{\mathrm{actual,\,i}}^{\mathrm{DHW}}) \cdot (t_i - t_{i-1}), \text{ if } T_{\mathrm{actual,\,i}}^{\mathrm{DHW}} < T_{\mathrm{low,\,i}}^{\mathrm{DHW}} \tag{4}$$

Where n is the amount of minutes included in the analyzed period, t is the time expressed in minutes, $T_{\mathrm{low}}^{\mathrm{SH}}$ and $T_{\mathrm{high}}^{\mathrm{SH}}$ are respectively the lower and higher dead-band limits. $T_{\mathrm{low}}^{\mathrm{DHW}}$ is the DHW comfort limit arbitrarily fixed to 42.5°C while $T_{\mathrm{actual}}^{\mathrm{SH}}$ and $T_{\mathrm{actual}}^{\mathrm{DHW}}$ are respectively the space heating and the DHW actual values.

Considering the summer season, the developed control logic for the DHW consumption described in section 3 allows a remarkable improvement in the water temperature profile stability together with a potential energy saving of about 6%. The dead-band deviation obtained with the improved logic is less than 0.5% of the DBD value obtained by the original control. The usage of the auxiliary heater is also drastically decreased over the summer season by more than 93%.

For the internal gain improvement potential study, the months of January and March have been considered as test periods. Fig. 3 shows the results of the comparison between the basic and the improved logic over a 24h period selected in the simulation month of March. As can be observed in Fig. 3a, the indoor temperature obtained by the basic controller is affected by the given internal gain profile and a room overheating effect can be identified. On the other hand, the improved control logic allows to better maintain the indoor temperature within the reference dead band of 21±0.5°C. Fig. 3b shows the corresponding results in terms of supply heating water temperature over the same 24h period where the improved logic is able to reduce the overheating effect by modulating the building heating curve.

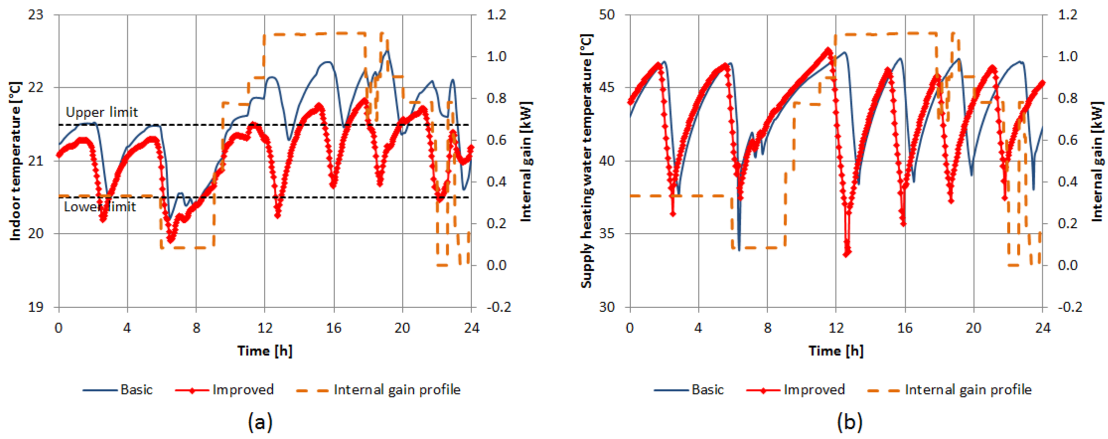

Fig. 3 Internal gain perfect prediction: comparison between the basic and the improved control logic with reference to (a) the indoor temperature and (b) the supply heating temperature.

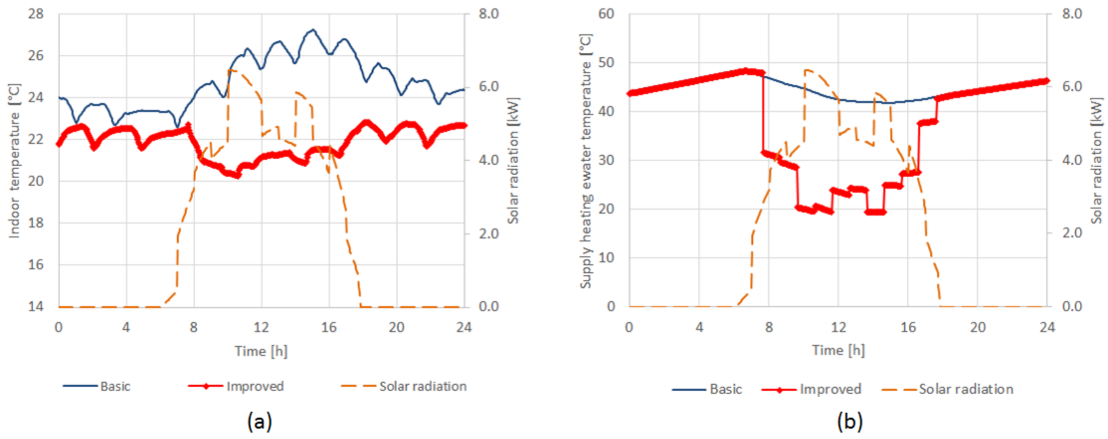

Fig. 4 Solar radiation perfect prediction: comparison between the basic and the improved control logic with reference to (a) the indoor temperature and (b) the supply heating temperature

The control logic based on the prediction of the ambient temperature have been specified for two possible operating modes. One mode has been set in order to maximizing the energy saving (*energy mode*) while the second has been set with the aim of minimizing the DBD parameter (*comfort mode*). Over the heating season period (from September to May) the results show a potential reduction in the usage of the auxiliary heater of about 10% in the *energy mode* and a decrease of the DBD parameter up to 88% when operating in *comfort mode*.

Fig. 4 shows an example of the simulation results obtained by exploiting the control logic based on the perfect prediction of the solar radiation. For a given period of 24h during the simulated month of March, as can be observed, the room temperature is affected by the incident total radiation and a room overheating effect can be clearly identified in Fig.4a. The improved control logic allows the modulation of the building heating curve in order to obtain a modified supply temperature profile (Fig.4b) and the mitigation of the room overheating effect. Over the entire heating season, the results show a reduction of the system energy consumption of about 15% while decreasing the DBD parameter of about 68%.

5. Conclusions

In this paper a system model is described and TRNSYS is used to dynamically model the whole system over a year. The heating system is based on a single speed ground-source brine to water heat pump unit, a thermal storage tank and an auxiliary heater. The basic on-off control logic adopted for both space heating and domestic hot water consumption is described and adopted as a benchmark. Additional input variables based on the forecast of domestic hot water consumption, internal gain, ambient temperature and solar radiation have been considered in order to investigate the energy saving potential of advanced control strategies that can be implemented in a heating system controller.

Different control objectives are discussed. The first control objective considers the potential maximization of the energy saving while the second aims to the maximization of the indoor temperature stability. A dedicated parameter is defined to discuss the deviation of the indoor temperature with reference to a given dead-band.

With the exception of the domestic hot water, the methodology adopted is based on parameter refinement procedures able to adjust the heating curve in order to obtain a required supply temperature consistent to the actual building heating demand. The corrective coefficients for the heating curve modulation have been refined by means of a trial and error procedure.

The overall results show an energy saving improvement potential from 6 to 15% with a considerable decrease of the indoor temperature deviation from the set-point and a significant reduction of the auxiliary heater usage.

Further work will aim to better investigate the enhancement potential given by the combination of the described control logic and the adoption of other system layouts including variable capacity heat pumps.

Acknowledgements

This work is related to the project "Smart Control Strategies for Heat Pump Systems" within the EffSys Expand program co-funded by the Swedish Energy Agency together with industrial project partners. The authors want to thank Danfoss Heat Pumps AB, IVT-Bosch, Nibe, Bengt Dahlgren, Nowab AB, ETM Kylteknik AB, Hesh Automation and ElectroTest AB for the support to this project.

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