HYDRAULIC BALANCE IN SMART HOMES
Using The KNX-standard for Performing Balanced Heating Conditions in Dynamic Load Situations

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Abstract: Efficient and clean energy consumption is not only an essential request towards industrial economics. This request also refers towards the residential building sector. There, the major share of energy consumption is caused by house and facility heating. In Germany, most heating systems consist of double-pipe, hot water systems. Due to the lack of hydraulically balanced system conditions, a potential of up to 15% energy-savings can be assumed. This paper addresses the use of KNX-technology (Smart Buildings) in residential buildings to ensure a dynamic adaption of hydraulic systems performance, in order to increase the heating systems efficiency. Therefor, a procedure of heating system segmentation into hydraulically independent units (meshes) is presented. This structure enables permanent control of adressable, net-based heating valve drivers in order to achieve balanced mass flow distribution over the whole facility. The dynamic hydraulic balance is achieved by positioning these valves according to heating loads, that are generated from the temperature settings in the corresponding rooms. The energetic advantages of single room heating control procedures, based on the application FacilityManager, is presented.

1 INTRODUCTION

Providing sufficient and clean energy is one of todays most challenging problems. Energy consumption as well as production strategies are forced to be aligned in many sectors. Facility management, residential housing, can contribute large potentials to decrease energy consumption. Thus, lower demands affect sourcing and production strategies. About 50% of the overall energy-consumption in Europe is caused by buildings/facilities. A share of about 70% refers to space heating. Thereby, the high share of out of date buildings and heating systems highlights those potentials. Invests in high efficient heat generators are deferred especially in the residential housing sector. Next to heat generation, the probabilities of energy savings in heat distribution systems are not used adequately. In the future, the importance of hydraulic balanced systems is expected to increase, due to tightened legal restrictions (German Department Of Justice, 2009). Conventional hot water heating distribution systems, such as double-pipe-networks, are technically mature in most systems. Their long durability delay important invests into modern hybrid systems. Such heating systems are operated in about 70% of all buildings in Germany. The highest share of those systems lack hydraulic balanced operating conditions (Guzek, 2010). These systems are an important opportunity for efficency decreasing measures.

The after-effects of imbalanced systems are delayed heat-up over the building, variable hydraulic conditions, increasing energy consumption (primary and secondary energy) and disturbing floating noises. In simulations, FELSMANN and HIRSCHBERG found out, that hydraulic imbalanced buildings cause 8% higher mass-flow-turnover than optimized buildings (Felsmann and Hirschberg, 2007) and (N. Fumo and Chamra, 2009). This additional turnover results in a 25% rise of electrical energy demand for the heating turnover pumps.

The allocation of space heating in most buildings is achieved by conventional thermostatic heating valve drivers (thv) and circulation pumps. Alternatively, thv can be replaced by motor valve drivers, that recieve their actuating variable from external systems. Such systems are provided by KNX-technology. KNX enables controlling local networks in a variety of functions (power distribution, heat-

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ing control, security installations and others). The VPN-based bus integrates sensors and actors within building networks and thus enables holistic control procedures. Current room temperature control systems anticipate many environmental parameters and self-adjust heat generator settings as well as heating valve settings within the rooms. Caused by numerous temperature settings through the users, the hydraulic conditions within a single pipe vary and influence the proper hydraulic supply of remaining heating devices within the same line (R.Yao and Steemers, 2005). Due to heterogeneous settings of different users, conventional measures of hydraulic balance fail to compensate dynamic changes of difference pressure, caused by the named reason. Via motor valve drivers on each heating device, configurated within bus structures, the valve settings can be used to compensate these dynamics. As far as the hydraulic specifications (i.e. difference pressures, characteristic diagrams of heating valves, valve driver ranges) of the pipes are known, the valve positioning can be controlled by a central facility server application. The current value of the drivers enable information about the hydraulic systems performance. Thus, different load scenarios of the heating system can be considered in the controlling algorithms for each room in a specific pipe and ensures dynamic hydraulic balance.

2 BUILDING SERVICES

For emphazising the potentials of integrated control and automation systems, the current situation of facility management, with respect to heating systems, is to be sketched. For presenting technical installations, the following nomenclature is set:

Table 1: Nomenclature.

Symbol	Meaning	Unit
c_p	specific heat	$kJ/Kg \cdot$ K
f	energy coefficent	n.d.
r_v	valve range	%
l	length	m
ν	flow velocity of water	m/s
$\dot{m}$	mass flow	Kg/s
P	pressure	Pa
ρ	(water) density	Kg/m^3
Q	primary energy	W
$\dot{q}$	heat flow density	W/m^2
ζ	pressure loss	n.d.

2.1 Conventional Building Services

Building automation, especially Smart Home infrastructures, is only about to begin dispreading the market. For about 10 years now, some applications for detached houses have been developed and installed. Volume services for residential buildings could not be found among the retailers portfolios (T. Teich, M. Zimmermann, S. Franke, F. Janh and M. Schrader, 2010). So far, most installations and their control systems have been conducted by companies of different crafts or branches and handicap integrative control procedures. In the field of heating, integrative building control was impossible to maintain, due to the following systems characteristics: Most heating systems consist of the modules heat generation, heat distribution and heat transmission (Seifert, 2009). Heat transmission appliances are structured according to the dwelling unit structure. Due to heterogeneous heat allocation, most heating systems work inefficiently (Guzek, 2010) and appear most notably in large heating systems (Felsmann and Hirschberg, 2007). About 70% of residential buildings are equipped with central heating systems with two-pipe installations (Guzek, 2010). Based on main heat distributing pipes (horizontal), numerous rising pipes supply the rooms of the buildings vertically. Each rising pipe distributes the corresponding heating devices with mass flow of hot water and represents a single mesh. These meshes mostly correspond with the vertical dwelling unit structure. Within a mesh, the hydraulic conditions vary according to: mesh-distance to circulation pump; storey height; components parameters; room utilisation. Within single dwellings, the user is capable to optimize utilisation towards cost-minimisation and comfort-maximisation. These local optima interfere and do not necessarily lead to an efficient heat supply over the meshes and the whole building. The determinants of the efficiency are primary and secondary energy. It is important to understand the interference between the required energy of the used energy carrier (primary), and the necessary electrical energy for controlling and distributing (secondary) the generated mass flows, according to the equation:

$$Q_p = \sum_j Q_j \cdot f_{pj} \tag{1}$$

Beside physical influences of the building (hull damping, internal heat transmission etc.), user settings determine the primary energy demand significantly (N. Fumo and Chamra, 2009). Due to technical standards in conventional space heating systems, there is a lack of information about user settings and their effects (thermal and hydraulic) within the distribution system. Individual control sequences and thus mass flow distribution are not aggregated for optimal operation. Hydraulic balancing of the heating systems is often used to achieve more efficient heat distribution. There are still about 90% of all operated systems, where such measures have not been conducted (Guzek, 2010) and (Szendrei, 2010). Standard procedures of hydraulic balancing cover hydrostatic adjustments for heating loads under extreme circumstances (full load). In this condition, the proper mass flow distribution can be obtained throughout the system by adjusting proper resistance at the heating valves (forward-motion pipe). Alternatively, resistors are inserted in the backward-motion pipe of the distribution system. This adjustment is legally forced by the DIN 18380 requirements. More realistic load profiles have to cover partial heating scenarios. In these cases, that occur throughout 95% of the heating season, significantly smaller mass flows have to be circulated by the distribution system. Besides meteorologic influence, the mass flow is object to dynamic user settings (R.Yao and Steemers, 2005). That way, the statically adjusted resistances are out of tolerance and do not ensure homogeneous mass flows. The effects of imbalanced working conditions are:

Thermal/Comfort Effects: delayed heat-up of rooms/dwelling, flow noises, declined control quality of thv;

Efficiency Effects: increased energy demand, increasing backward-motion water temperatures, rising operating expenses, decreasing system durability.

In order to achieve adequate hydraulic conditions, the control system for space heating can be used. To anticipate the hydraulic interferences between the dwellings, it is essential to control the mass flow of each mesh that supplies different heating devices over the storeys. Therefore, the configuration of the KNX-network must consider the systems installation of rising pipes and its attached devices. So far, mass flow specifications regarded the entire pipe setup within a closed heating system according to:

$$\dot{m} = \frac{\sum \dot{Q}}{c_p \cdot \triangle \vartheta} \qquad (2)$$

and

$$\triangle p = \sum (R \cdot l) + \sum (\zeta \cdot \frac{\nu^2 \cdot \rho_m}{2}) \qquad (3)$$

Since smaller pipe sections are more simple to control and to calculate, such entire systems can be segmented into meshes. Each rising pipe, supplying the above storeys/rooms with water, may represent a single mesh. At the main distributing pipe, a difference pressure controler disconnects the meshes from the hydraulic mainframe. The calculations and conditions follow the shown procedures from equations 2 and 3.

2.2 KNX-based Building Services in Space Heating

With these information, different load scenarios can be modelled. A dynamic control within the given structure with independent hydraulic mesh conditions is enabled. Because of reducing the number of attached heating valves, the mass flow conditions are to be assumed more effectively. Thus, possible load scenarios can be modelled and deposited for facility server applications. According to heating demand in the meshes, valve ranges can be tuned in to dynamically balance the meshes mass flow and ensuring adequate heat supply. The advantage of this approach is the coverage of static and dynamic load profiles. In general, heating valves in lower storeys require a higher hydrostatic resistance (bigger valve range). In accordance with the number of storeys, the necessary resistance is to be decreased. The implementation of this control requires accurately working valve drivers. These are to be found among KNX-based, continuously controlled drivers.

As demonstration and try-out objects, two multi-storey residential buildings have been equipped with KNX-based actors and sensors. Applications of heating control, electric appliance control, protection/security control and others are installed. Besides control procedures, the KNX-network enables visualisation, remote operations, flexible billing and individual setups of the installed components (T. Teich, M. Zimmermann, S. Franke, F. Janh and M. Schrader, 2010). In the field of heating control, the existing building service hardware (i.e. heating devices, pipes, heat generator) did not have to be renewed. The functionality of heat generation and distribution hardware was available for restarting it with KNX-based valve drivers. Thus, integrative control procedures of room temperature and heat generator settings are enabled throughout the building. The valve drivers are addressable, continuously controllable units with a total range of 3 millimetres, that replaced the existing thermostatic valves. With such drivers, conventional valve-cores became easy to control. Inside the buildings, the equipment is linked via Ethernet. The communication between facilities is transacted over VPNs. Those provide a private communications network over a shared public network infrastructure such as the Internet. Basically, there are three types of virtual private networks: Remote access VPN connection (end-to-site), Branch Office VPN connection (site-to-site) and Extranet VPN connection (end-to-end) (T. Teich, M. Zimmermann, S. Franke, F. Janh and M. Schrader, 2010). The demonstration objects are interconnected by a site-to-site VPN connection. Regarding security issues, VPNs provide high protection against external access.

3 IMPLEMENTATION OF SINGLE ROOM TEMPERATURE CONTROL

3.1 Operational Description

Conceptual core of the heating control is maintaining single room temperature control. This ensures the appropriate comfort, required by the user. The aim of the control is to harmonize the resulting differences in mass flow, that are caused by diverse, interfering user temperature settings. KNX components for single room control are a temperature sensor, a heating actor and a heating device valve driver. This setup refers to a single room with one heating device (Szendrei, 2010). The desired set temperature is specified as a temperature profile in the facility server by the user. The value of the actual temperature is compared to the set temperature value by the installed sensor via telegram-communication. Contrary to thermostatic valve controls, the sensor is positioned on the heating device facing wall. That is to provide pure values of the actual operating temperature. As an offset for the single room temperature control $|\vartheta_{set} - \vartheta_{act}| \geq 0.5K$ has been adjusted. This offset prevents the control system from oscillating (GIRA, 2006) and assures satisfactory thermal comfort for the user (Guzek, 2010). The facility server based controller tracks the actual temperature values of each room by requesting KNXnet/IP-telegrams from the devices. This communication is transacted full-time in a two minute frequency. The exchanged information is then used to measure the offset. In case of an actual temperature being more than 0.5K lower than the set value, a heating demand for the corresponding room is generated. In such cases, a decision variable *HD* is set true. According to the combinations of heating demands within a mesh, specific load profiles and assigned valve ranges are deposited. Table 2 presents all possible heating load profiles and the assigned valve ranges for a dynamic hydraulic balance in a three storey mesh (Szendrei, 2010).

According to the measured temperature offset, *HeatingDemand* ist evaluated. The ranges for the meshes valves are then assigned to the heating actors and valve drivers via KNXnet/IP-telegrams. The valve driver (re-) positions itself (corrective action) and sustains that position until the next telegram request. During a control sequence, only one load profile is valid. The valve ranges are calculated on the basis of their specific character diagrams. From the difference pressure calculation (see section 2.1), the values of choking hydraulic resistance are known. Over each mesh, these values can be expressed as ratios towards the total difference pressure. Within a mesh, each integrated valve produces an individual difference pressure. Thus, the corresponding ratios can be used to determine the valve ranges, that create the required choking resistance, resulting from valve coefficients:

Table 2: Space heating load profiles within a valve mesh.

decision variabe *HD*			valve range r_v		
gnd fl.	1st fl.	2nd fl.	r_{GF}	r_{1st}	r_{2nd}
0	0	0	0	0	0
0	0	1	0	0	100
0	1	0	0	100	0
0	1	1	0	75	100
1	0	0	100	0	0
1	0	1	75	0	100
1	1	0	75	100	0
1	1	1	65	75	100

$$k_v = \dot{V} \cdot \sqrt{\frac{1bar \cdot \rho}{\triangle p_v \cdot 1000kg/m^3}}\ [m^3/h] \qquad (4)$$

and

$$\dot{m} = \rho \cdot \dot{V}\ [kg/h] \qquad (5)$$

According to the control frequency of two minutes, the valve positioning assures a dynamic balancing of mass flow. That way, the hydraulic efforts of the heating system can be reduced by about 8% (Guzek, 2010). Consequently, the secondary energy consumption can be derated 25%, with regard to the simulations of GUZEK. Those estimations are to analyse by evaluating the heat flow density within the different rooms in one mesh (Thron, 2001). Equal values thereby indicate proper hydraulic conditions. To efficiently implement the control system with KNX-based valve drivers, their metering characteristics are to consider.

3.2 Metering Characteristics of Available KNX-based Valve Drivers

For bus-based applications (KNX), different valve drivers are available. Because of the requirements towards high control quality for space heating, not all available drivers are suitable. To ensure effective, dynamic adaption of the heating device valve positions, the parameters operating speed and control frequency are to harmonize. As a matter of fact in residential facility management, procurement, installation and servicing costs have to be kept low and are used as feasibility criteria. Reliable devices with the following metering characteristics are available as thermal drivers and electromotive drivers.

3.2.1 Thermal Valve Drivers

These discontinuously acting drivers usually work as two-position controllers. Heating device valves can be positioned to the opened and closed position (Zou, 2008). The control signal for the drivers is generated by the facility server. After its transaction to the KNX-based heating actor, a voltage is triggered to the driver. This voltage is used to heat-up a thermal resistor, that devolves its extension onto the valve. This technology is comparatively cheap. Major disadvantage is the inaccurate controlling of the valve motion. This is caused by the required heat-up time $(t_1 - t_2)$, which is varying under certain circumstances. Furthermore, the average heat-up time from two minutes exceeds the available cycle time of the control procedure. Regarding these characteristics, accurate valve positioning with two-position controllers seems impossible. Another possibility is controlling thermal valve drivers through pulse width modulation (PWM). That modulation can be achieved by time-dependent applying of voltage to the valve driver. The pulsing periods have to consider heat-up as well as valve motion duration, in order to maintain a virtual continuous control. The modulation probabilities of the virtual continuous controller require instant and fast valve motions. Due to the components characteristics, motions are delayed and unsteady. The aim of dynamic and high frequency mass flow adaption is not to be implemented with the named drivers.

3.2.2 Motor Valve Drivers

Alternatively, electromotive valve drivers can be used. There are many suppliers who offer these drivers with KNX-interfaces. The metering characteristic of such components is continuous control. In general, two control types are common. First: voltage-proportional controllers. These drivers are supplied with a voltage from 0.5 to 10 V. According to the applied level, the valve driver conducts a forward motion that is devolved onto the valve (Szendrei, 2010). In addition to the bus cable, a power line has to be installed for implementing this technology. Second control type is a binary coded positioning system within the drivers. A range recognition system precisely positions the valve, according to the incoming control signal. The signal is transmitted via KNXnet/IP-telegrams. The telegrams contain a two bit message, that represent the required valve setting. Beside the accurate positioning capabilities, the small effort for installation is to be highlighted. Only bus cables are to be installed throughout the building. One disadvantage of this technology are higher procurement costs. To achieve an optimal technical infrastructure, the trade-off between metering characteristics and procurement, installation and servicing costs of the valve drivers had to be evaluated. Regarding the high controlling potentials of electromotive drivers and their higher durability, this technology was chosen for implementation.

4 RESULTS

As a reference object, a multi-storey building with 18 dwellings has been equipped with KNX-technology. Within the building, appliances of space heating, electromotive supply, presence detection, security and others werde installed. The space heating is implemented according to the shown concept. For the installation periphery, more than thirty single components have been installed in every 2- or 3-bedroom dwelling. Another dozen components assure the systems operation and control as centralized control devices in the basements of the facilities. As a control system, the application *FacilityManager* has been implemented. This application detects and evaluates the heating offset via temperatur sensors in a two-minute frequency. The load profiles for range adjustment of the heating valve by motor drivers were found according to the valves characteristics. Since usage of space heatings vary between the dwellings, identical heating scenarios were modelled. First evaluations of the convergency of actual and set temperature values indicate a uniform heat-up of the dwellings within the meshes. More detailed analyses are to be carried out in the upcoming heating season. Therefor, the differences in room-heat up have to be evaluated according to:

$$\frac{\dot{q}}{\dot{q}_{hd,ref}} = \frac{k_{hd} \cdot \triangle t}{k_{hd,ref} \cdot \triangle t_{ref}} \qquad (6)$$

The density of heat flow thus indicates hydraulic undersupplies. As a reference (ref) for the homogenous heat transmission, the heating devices (hd) in the ground floors are assumed. This is caused by their hydraulic advantaged location related to the above installed devices. Furthermore, the electrical power consumption of the circulation pump was measured.

In comparison to similar workloads, measured before the systems renewal, first savings could be detected. For further proof, the circulation system will be compared to a hydraulically non-balanced system with similar parameters.

5 CONCLUSIONS

Energy savings, especially primary energy in space heating, can decrease general energy consumption. These large potentials are caused by the high share, of improvable heating systems. In about 90% of these buildings in Germany, heat distribution and transmission components lack hydraulic balanced operating conditions. By launching smart building infrastructures, such as the KNX-standard, new control scenarios for various building services can be implemented. The application of VPN-connected control components enables hydraulic balancing while maintaining single room temperature control throughout (large) domestic buildings. To assure homogenous mass flow allocation, the heat distribution system was segmented into hydraulically independent meshes. Within each mesh, KNX-based heating valve drivers are positioned in accordance to the corresponding heating load profile. The determination of load profiles is achieved by requesting actual temperature values via KNXnet/IP telegrams. The values from all rooms are assigned to the specific mesh structure. In different trials, electromotive valve drivers were found to act most feasible while affording high durability. Such drivers are characterised by fast and precise range adaption. The installation effort for the presented infrastructure remains comparatively low. First energy savings, caused by hydraulic balanced heat-up of the building, were measured at the circulation pump. Because of the balanced hydraulic workload, the electric energy consumption could be reduced. Due to mild weather conditions, these savings in electric power consumption for the distribution system, are to evaluate as initial estimations. High decomposition measurements of the temperature spreading (forward-backward motion) will indicate the homogenous heat distribution over the meshes. These measurements are initialized for the upcoming heating season. Detailed calculations and utility analyses are tasks for the further project work. Regarding the feasibility of other building services, that have to be integrated into the KNX-network technology, more flexible and comfortable control procedures can be established. For instance, the interference of light irradiation, heating and ventilation can be integrated into automated control scenarios for large facilities.

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