ENERGY EFFICIENCY OF HYDRONIC SPACE-HEATING DISTRIBUTION SYSTEMS IN SUPER-INSULATED RESIDENTIAL BUILDINGS

Laurent Georges[1], Tomasz Iwanek[1], Martin Thalfeldt[1]
[1]Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Abstract

In space-heating (SH) dominated climates, super-insulated building envelopes, such as passive houses (PH), are often promoted to drastically reduce SH needs. Using hydronic SH distribution in PH, thermal losses from pipes become a relatively large source of internal gains. Nevertheless, buildings with super-insulated envelopes have high utilization factors of heat gains so that the resulting SH distribution efficiency is currently unknown. The article investigates this energy efficiency with dynamic simulations (here using IDA-ICE) and a detailed modelling of the SH distribution system. Such detailed studies are rarely found in the scientific literature where generally the physics is modelled in an oversimplified way. The performance of standard and simplified SH distribution loops are compared and discussed. It is confirmed that the fraction of uncontrolled thermal losses from the SH distribution system is large (up to 50% of the heat delivered to the system can be emitted by pipes), but that the distribution efficiency is nonetheless kept high (above 90%). Compared to other forms of energy losses in super-insulated buildings, the present work suggests that the increase of energy use caused by thermal losses from the hydronic SH distribution remains a secondary problem.

Introduction

In space-heating (SH) dominated climates, such as Scandinavia, building regulations and standards promote highly-insulated buildings to drastically reduce SH needs. A good example is the passive house (PH) standard, which requires for so-called *super-insulated* building envelopes. This standard has been adapted to many locations, such as Norway with the NS3700 standard (Standard Norge, 2010). Most existing concepts and pilot buildings for Norwegian Zero Emission Buildings (ZEB) are also based on super-insulated building envelopes (Dokka et al., 2013; Houlihan Wiberg et al., 2014).

Compared to older buildings with a significantly lower insulation level, super-insulated building envelopes introduce new challenges and opportunities for the SH distribution system:

- Firstly, internal gains play a major role to counterbalance the limited amount of thermal losses of the building envelope. Thermal losses from the water-based distribution system become relatively more important so that their contribution as internal gains should be properly evaluated.
- Secondly, the SH distribution system can in principle be simplified in PH (Feist et al., 2005). As the building is super-insulated, it is indeed not necessary to place a heat emitter in front of each window to prevent cold draft, or even in each room. This simplification of the SH distribution forms the basis of the German definition of the PH standard (Feist, et al., 2005), where the initial motivation for the simplification is reduction of investment costs. Typically, this can be done by reducing the number of heat emitters inside the building. In the present study, the case of one radiator per floor is investigated while the cases of air-heating or wood stoves have been already studied in other Norwegian research works (Georges, Berner, et al., 2014; Georges, Skreiberg, et al., 2014).
- Thirdly, super-insulated building envelopes are better heat storages, characterized by longer time constants and thus higher utilization factors of gains (CEN, 2008a).

Combining these three elements, calculating the resulting energy efficiency becomes less evident. Keeping the SH distribution network unchanged, heat losses from the distribution system are relatively more important in super-insulated buildings but these buildings have a better capability of utilizing these losses for SH. In addition, the SH distribution loop can be simplified to reduce the heat losses for the SH distribution system. The objective of the present work is to investigate the influence of the distribution system design on the energy efficiency in the context of super-insulated buildings. To the authors ‘knowledge, this question has never been addressed from the perspective of super-insulated buildings in previous works.

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Figure 1. Floor plan of the terraced PH for the basement, ground and first floors, respectively.

In general, few studies investigating SH distribution efficiency in detail have been conducted. The reason might be the complicated dynamic phenomena of distribution losses. Until now, building performance simulation (BPS) tools typically have not supported the detailed modelling of the heating system with pipework, thermostatic valves and radiators, which have continuously changing flow rates and temperatures. The work of Maivel et al. (Maivel & Kurnitski, 2014) is an exception, where the emission and distribution efficiency of low-temperature radiators has been investigated for nearly zero-energy buildings using detailed dynamic simulations (IDA-ICE). In practice, SH distribution losses are generally evaluated in a simplified way, typically using tabulated distribution efficiencies. In Europe, these tabulated values are usually given in national standards, see e.g. NS3031 (Standard Norge, 2014), while the overarching EN 15316 standard (CEN, 2007) provides guidelines to establish these tabulated distribution efficiencies. Detailed evaluation methods are nonetheless already introduced in standards, each of them having different levels of modelling simplification, such as the EN 15316 (CEN, 2007; Olesen & de Carli, 2011), prEN 15316 (CEN, 2014) or prNS3031 (Standard Norge, 2014). These detailed evaluations are most often not applied, or not supported by default, in BPS packages.

Following the work of Maivel et al., the present contribution also investigates distribution losses using dynamic simulations (IDA-ICE) with a detailed modelling of the SH distribution system. Compared to this previous work, the present article rather focuses on the influence of the building insulation level and on the design of the SH distribution system. The need for BPS tools that model in detail the SH distribution system in super-insulated buildings is questioned. The paper focuses on the energy efficiency of the SH distribution. The ability of a simplified SH loop to provide for the required thermal comfort in each zone is not covered here (see e.g. Georges et al. (2016), Håheim (2016)).

Methodology

Building test case

The test case is a terraced house from the Miljøbyen Granåsen project located in Trondheim, which is currently the largest PH construction project in Nordic countries. Miljøbyen Granåsen is developed by Heimdal Bolig and is also part of the EBLE, Concerto and Eco-city research projects. The terraced house with heated area of 142.5 m² consists of three storeys as shown in Figure 1. It is a timber frame construction except for the basement, which was built with concrete. In that respect, the building thermal mass is characterized as light (CEN, 2008a). The balanced mechanical ventilation has a heat recovery unit and provides for an air change rate (ach) of 0.52/h. The electric resistance further preheats ventilation air with a set-point temperature of 16°C. Thermal properties of the PH building are listed in Table 1.

Table 1: Thermal properties of the three building cases.

Component	PH	TEK10	TEK87
Extern. wall U-value [W/m².K]	0.15	0.22	0.35
Roof U-value [W/m².K]	0.06	0.18	0.23
Basement U-value [W/m².K]	0.10	0.18	0.30
Infiltration n50 [1/h]	0.60	2.50	3.00
Windows U-value [W/m².K]	0.80	1.20	2.10
Doors U-value [W/m².K]	0.80	1.20	2.00
Norm. cold bridges [W/m².K]	0.03	0.03	-
Heat recovery rated temperature efficiency (EN 308)	88%	70%	-
SH needs [kWh/m².year]*	17.1	33.5	87.9

**According NS3031 using the entire building block (4 dwellings) and intermittent SH (i.e. temperature setback during nighttime).*

To investigate the influence of the building thermal insulation on the performance of the SH distribution system, two alternative cases are considered. One corresponds to the minimal requirements of the current Norwegian building regulation, TEK10 (KRD, 2010), and the second to the requirements of 1985, TEK87 (KRD, 1984). Typically, natural ventilation was used in TEK87 buildings. For the sake of the simplicity, it was modelled as balanced mechanical ventilation with a heat recovery efficiency of 0% and no air pre-heating. Standard internal gains for persons, lighting and

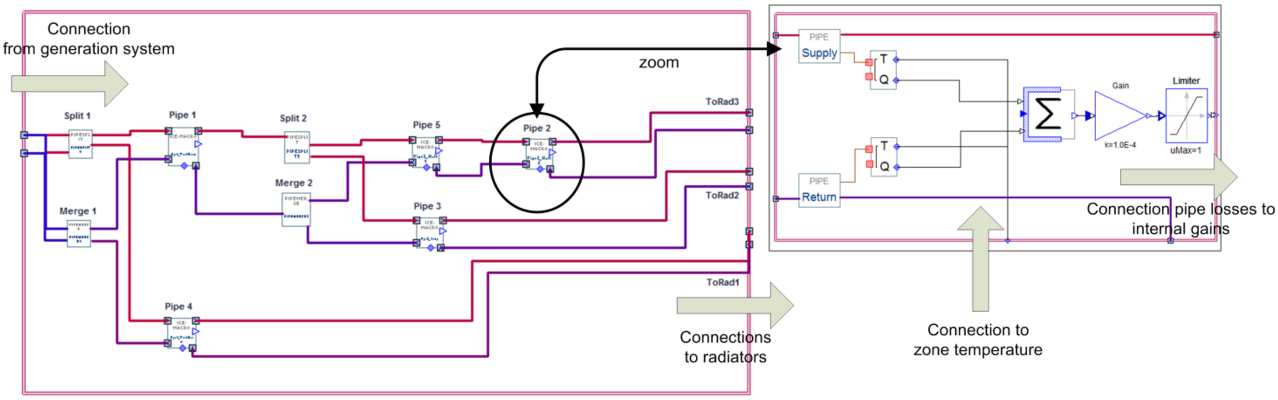

Figure 2. Example of IDA-ICE macro developed to model the simplified SH distribution system: a first layer combines a supply and a return pipe segment (right), the second layer (left) combines these two-pipe components into a network.

equipments have an average value of 4.0 W/m² (Standard Norge, 2014).

Trondheim is located in Norway (63°30' N, 10°22' E) and has a subarctic climate with severe winters (Köppen-Geiger classification Dfc). The SH design outdoor temperature (DOT) is -19°C, the yearly-averaged outdoor temperature 5.1°C and the yearly-averaged horizontal solar irradiation is 101.6 W/m².

Definition of the SH distribution loop

The nominal SH power (Pn) for each room has been computed using the detailed building model. Following the standard design procedure in Norway (Standard Norge, 2003), the power is evaluated during steady-state regime with a constant DOT without solar or internal gains.

Based on nominal power, three SH distribution loops have been designed using two-pipe connections. The *standard loop* has one radiator in each room except for the technical room. *Simplified loops* have only one radiator per floor (i.e. the basement, the living room and the corridor in the first floor). One version has pipes mainly crossing non-heated rooms (Type 1), meaning the corridor on the ground floor and the technical room, while the second version has pipes crossing heated rooms only (Type 2). The total length of pipes for the standard loop is 38.55 m and 18.8 m for both simplified loops. This is comparable to the default pipe length for standard and simplified loops proposed in the prNS3031 (Standard Norge, 2014). By definition, simplified loops are only applied to the test case at PH insulation level.

Two design distribution temperatures (T_{dist}) are considered: 60°C/40°C and 40°C/30°C. Nevertheless, the TEK87 house can only accommodate a 60°C/40°C distribution loop, as 40°C/30°C would lead to radiators with prohibitive dimensions. During operation, a weather-compensated heating curve is applied. For each case, the diameter of each pipe segment is evaluated in detail using standard design criteria, including linear and singular pressure losses. The smallest pipe diameter that simultaneously generates a pressure drop lower than 100 Pa/m and a water velocity below 0.5 m/s is selected, with an additional constraint that the pipe should have a minimal internal diameter of 8 mm. The influence of pipe thermal insulation is investigated by comparing cases without insulation and with 19 mm Armaflex® insulation (thermal conductivity λ = 0.037 W/m.K).

Modelling of the building and the SH distribution

Multi-zone building simulations have been performed using the BPS software IDA-ICE version 4.7.1 (EQUA, 2016). Parameters for the building envelope and ventilation system have been defined in IDA-ICE using as-built documents. The discharge coefficient (C_d) for the bidirectional airflow in open doorways is taken at 0.65. SH needs have been validated against the value computed using SIMIEN (ProgramByggerne, 2012). SIMIEN is the BPS software that has been used during construction to prove that the building complies with the Norwegian building regulation. Comparison with measurements has shown that this IDA-ICE model is able to well reproduce the temperature differences between rooms during the SH season (Håheim, 2016). Even though this comparison has not been done using standard calibration indexes, such as the NMBE and RMSE (Claridge, 2011), the building model is considered validated enough for the purpose of the study.

The standard IDA-ICE interface already includes a detailed radiator model, which considers both thermal and hydraulic aspects. As emission efficiency is not the subject of the work, thermostatic valves (TRV) are modelled using a PI control directly adapting the mass flow through the radiator (which is in practice equivalent to a perfect control with a valve authority of 1.0). Consequently, the mass flow through each radiator changes continuously during simulation as a function of the room instantaneous SH needs. The radiator geometry is embedded in the 3D virtual model of the building. This enables the radiator model to account for the enhanced thermal losses through the wall at the back of the radiator. Stratification losses are not modelled.

Each pipe segment of the distribution network was created manually in the advanced interface of IDA-ICE (so-called "schematic") where users can combine components into a system in an equation-based environment, see Figure 2. Each time a distribution pipe crosses another zone or connects a pipe junction, a new pipe segment (or component) was created in the network model. The implementation of each network (i.e. standard and simplified loops) in IDA-ICE has been validated by comparing the water temperature and mass flows at each node of the network with an equivalent implementation in Matlab®.

Thermal losses from each pipe segment are evaluated using the ISO12241 standard (ISO, 2008) assuming a steady-state heat exchanger model and a mean logarithmic temperature difference (LMTD). The overall heat transfer coefficient (U_w) between the water in the pipe and the pipe environment is assumed constant. Two different U_w have been evaluated for the two design distribution temperatures (60°/40°C and 40°C/30°C). U_w combines both the convection and the thermal radiation towards the room. Defined in terms of inside pipe area, U_w is evaluated using:

$$U_w = \frac{1}{\frac{1}{h_{c,in}} + \frac{r_{in}}{\lambda} ln\left(\frac{r_{out}}{r_{in}}\right) + \frac{r_{in}}{r_{out}} \frac{1}{h_{tot,out}}} \tag{1}$$

where r_{in} and r_{out} are the internal and external pipe radius, respectively. The convection coefficient ($h_{c,in}$) for a fully turbulent developed flow within a circular pipe is evaluated using the Dittus and Boelter correlation (Winterton, 1998). For the external airflow, the convection coefficient ($h_{c,out}$) is estimated using the Churchill and Chu correlation (Churchill, 1975) for a free convection around a long horizontal cylinder. The heat transfer coefficient for radiation ($h_{r,out}$) to the room is evaluated analytically assuming that dimension of the pipe is small compared to the room geometry. The radiation transfer rate is then only dependent on the area of the pipe external surface, its emissivity (ε) as well as the wall and duct surface temperatures (Incropera et al., 2007). The external heat transfer coefficient ($h_{tot,out}$) in Eq. (1) combines $h_{c,out}$ and $h_{r,out}$. Consequently, it is accurate when the difference between the room air and the wall temperatures is small (compared to the pipe external temperature). The heat emitted by the pipe segment Q_w to the room is evaluated using

$$Q_w = U_w(2\pi r_{in} L)\, LMTD(T_w, T_a) \tag{2}$$

where L is the pipe length, T_w the water temperature and T_a the room air temperature. The heat Q_w is injected into the room model as an internal gain both in form of convection and radiation according to the ratio between $h_{c,out}$ and $h_{r,out}$. Pipes have no physical location in the 3D virtual model of the room so that radiative gains are distributed between surfaces in an area-weighted manner. The overall heat transfer coefficients (U_w) computed using this method gives values comparable to the default values of prEN15316-3:2014 (CEN, 2014). The linear heat losses (Q_w/L) are also comparable to values reported in the standard.

Performance indicators

The performance of SH distribution systems is mainly compared using two monthly (or yearly) indicators:

1. The **fraction of thermal losses (ξ)** is the ratio between monthly (yearly) thermal losses emitted from the distribution system (Q_{loss}) and the monthly (yearly) energy delivered to the distribution loop by the heat generation system (Q_d). Q_d will be here termed “energy use”, a terminology that is only correct if the generation efficiency is assumed to be 100% (CEN, 2008b).
2. The **distribution efficiency (η_d)** is by definition the ratio between Q_d computed without pipe losses and Q_d computed with pipe losses. This last indicator also translates the amount of thermal losses that has been usefully recovered for SH.

For the sake of the simplicity, a constant indoor temperature set-point of 21°C is applied for all cases. This assumption is not expected to have a major influence on results and conclusions.

Analysis and discussion of results

The performance of the different SH distribution systems is firstly compared in terms of distribution efficiency (η_d), using a same set-point temperature for each radiator. In that case, the temperature in rooms without radiator is different between SH distribution systems. Therefore, this effect is accounted for in a second step where a minimal temperature is imposed in all rooms.

Distribution efficiency

The distribution efficiency is investigated in successive steps. Firstly, the case of the 60°C/40°C standard loop without pipe insulation is shown in Figure 3 for the three performance levels of the building envelope.

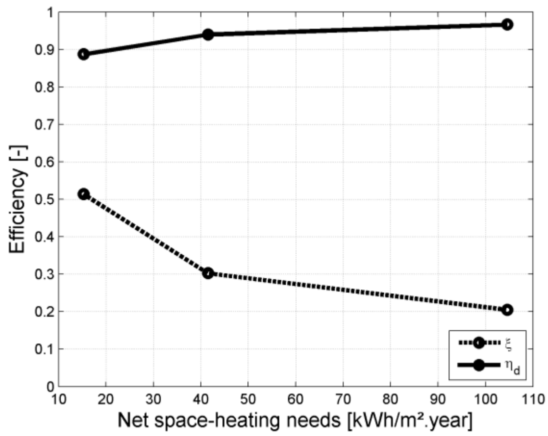

Figure 3. Yearly performance of the 60°C/40°C standard distribution loop without pipe insulation for the three buildings (with internal doors closed).

The share of pipe losses (ξ) has a moderate value of 20% for the TEK87 house. This value increases progressively to 30% for the TEK10 house. When the building performance is further improved to PH, ξ increases to 50%. As the utilization factor of gains is high in PH, a significant amount of these losses is recovered usefully.

Table 2: Performance of the SH distribution system with closed and open internal doors (21°C set-point temperature only applied in rooms equipped with a radiator).

				Internal doors closed		Internal doors open	
House	**Loop type**	**Temperature**	**Pipe insulation**	ξ	η_d	ξ	η_d
TEK87	Standard	60°C/40°C	No	0.205	0.967	0.202	0.985
			Yes	0.064	0.989	0.061	0.994
TEK10	Standard	60°C/40°C	No	0.303	0.940	0.278	0.987
			Yes	0.105	0.980	0.092	0.996
		40°C/30°C	No	0.193	0.957	0.167	0.992
			Yes	0.067	0.986	0.056	0.998
PH	Standard	60°C/40°C	No	0.514	0.887	0.495	0.953
			Yes	0.213	0.957	0.196	0.985
		40°C/30°C	No	0.330	0.929	0.308	0.975
			Yes	0.123	0.975	0.111	0.993
	Simplified (Type 1)	60°C/40°C	No	0.311	0.906	0.279	0.961
			Yes	0.124	0.968	0.096	0.990
		40°C/30°C	No	0.200	0.941	0.165	0.983
			Yes	0.083	0.980	0.055	0.996
	Simplified (Type 2)	60°C/40°C	No	0.382	0.992	0.228	0.992
			Yes	0.137	0.999	0.107	0.996
		40°C/30°C	No	0.237	0.992	0.194	0.995
			Yes	0.088	0.999	0.062	0.999

Nevertheless, from the TEK87 to the PH building, the distribution efficiency (η_d) is decreased from 97% to 88%. This decrease is significant but rather limited compared to the increased share of pipe losses (ξ).

Secondly, some measures can be taken to improve η_d, such as the pipe insulation or the reduction of the distribution temperature. Results are reported in Table 2. A distinction is made between closed and internal doors. With open internal doors, internal gains, such as pipe losses, will lead to a lower temperature increase in rooms than with closed doors due to the large bidirectional flow in open doorways. The resulting distribution efficiency (η_d) is then higher. This effect is more important with a higher share of internal gains, typically with high ξ. In Figure 4, a good correlation is found between ξ and the change of η_d between closed and open doors, regardless of the insulation level or distribution loop. It also gives an idea about the sensitivity of η_d to the user behaviour.

Compared to the baseline case with a 60°C/40°C loop without insulation, the standard loop has a better distribution efficiency using 40°C/30°C. Nonetheless, the pipe insulation has a more drastic influence on losses. Combining both effects, the η_d of a standard loop may reach 97-99% in a PH. This leads to the original conclusion than standard distribution loops can still be implemented in PH if measures are taken to limit losses from pipes.

Regarding the performance of the simplified distribution loops, cases with distribution pipes crossing non-heated zones (Type 1) and only crossing heated zones should be distinguished (Type 2). It is here assumed that the set-point temperature of 21°C is only applied to the zones equipped with a radiator. The temperature in the rooms without radiator is free-floating. With loop of Type 1, the share of losses (ξ) is reduced compared to the standard loop and kept at a level equivalent to the TEK10 building. In the PH case, the distribution efficiency (η_d) of the Type 1 loop is only slightly better than the standard loop because it is here considered that the temperature increase generated by losses emitted in non-heated zones does not add any value. This effect is obviously reduced if internal doors are open. Regarding the loop of Type 2, thermal losses from pipes are emitted in heated zones, a solution that gives very high efficiency (> 99%) whatever the distribution temperature level, the opening of internal doors, or the pipe insulation level. In other words, the simplified loop has a very high distribution efficiency and is more robust to design parameters than the standard loop, if location of pipes is selected carefully.

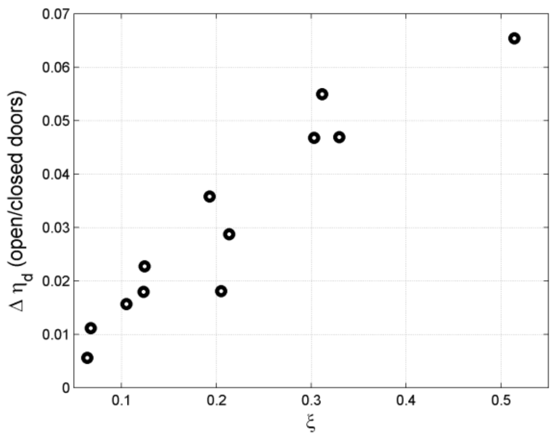

Figure 4. Correlation between the fraction of losses (ξ) and the variation of distribution efficiency (η_d) between open and closed doors.

Simplified versus detailed modelling

Two common simplified approaches to account for the SH distribution losses are now introduced and compared to the detailed model: tabulated data of NS3031 and using a fixed fraction of thermal losses (ξ).

The Norwegian standard NS3031 (Standard Norge, 2014) evaluates the energy use of buildings and resorts to tabulated distribution efficiencies. They are given as a function of the building type, the insulation level of pipes, as well as the distribution temperature, but regardless of the insulation level of the building, see Table 3. These tabulated efficiencies are very close the TEK10 values computed using the detailed model, with a maximum difference of 0.02. Nevertheless, these values are not representative for the other cases (TEK87 and PH) as well as for the simplified distributions.

Table 3: Tabulated distribution efficiency of NS3031

Temperature	Pipe insulation	η_d
60°/40°C	No	0.92
	Yes	0.96
40°C/30°C	No	0.94
	Yes	0.97

By default, IDA-ICE enables to account for the SH distribution losses by introducing the yearly fraction of thermal losses (ξ) as an input parameter. The instantaneous heat delivered to radiators is then increased by this factor to calculate the instantaneous energy use. The corresponding losses are introduced as internal gains distributed uniformly in all zones. Assuming ξ known, this method is here compared to the detailed evaluation. For the case of the standard distribution loop with a weather-compensated distribution temperature, the distribution efficiency (η_d) computed by both approaches shows a good agreement, even on a monthly basis, see e.g. Figure 5. In that case, the knowledge of the yearly fraction of thermal losses (ξ) is enough to determine the η_d. As ξ is rather constant throughout the SH season, its value could be pre-evaluated with a dedicated software in a decoupled way. Alternatively, a sensitivity analysis to the input parameter ξ could be done in IDA-ICE.

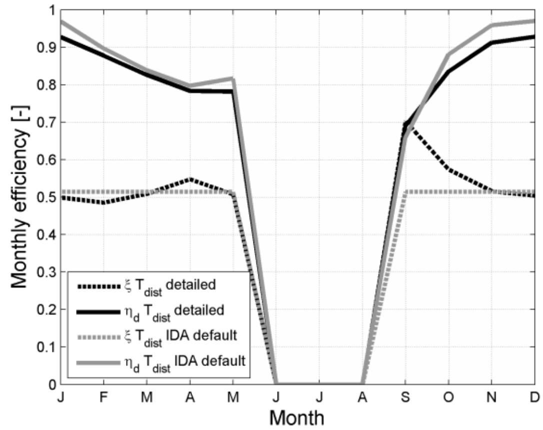

Figure 5. Monthly performance of the 60°C/40°C standard distribution loop in the PH without pipe insulation, detailed modelling versus default IDA-ICE modelling (with internal doors closed).

Nevertheless, the accuracy of the simplified method decreases when the hypotheses behind the simplification are no longer valid. For instance, a constant water distribution temperature would lead to larger variations of ξ during the SH season, or the simplified distribution generates by definition thermal losses that are not distributed uniformly inside the building, see Table 4.

Table 4: Default IDA-ICE model compared to the detailed model for the 60°C/40°C distribution loop without pipe insulation in the PH.

Loop type	Temperature	η_d (detailed)	η_d (default)
Standard	Variable	0.89	0.92
	Constant	0.80	0.87
Simplified (Type 1)	Variable	0.90	0.94
Simplified (Type 2)	Variable	0.99	0.92

Overall energy efficiency

The previous section only focused on the distribution efficiency (η_d), by applying a constant set-point of 21°C in rooms equipped with radiators. Nevertheless, standard and simplified loops lead to different temperatures between rooms inside the building. To investigate the overall energy efficiency, the energy use of the different distribution systems should be compared for a same thermal comfort. One should distinguish between two scenarios:

1. Firstly, the user wants 21°C in each room, equipped with radiator or not. With a simplified SH distribution, the set-point temperature in rooms

equipped with radiator should be increased above 21°C in order to ensure 21°C in rooms not equipped with radiator. With simplified distribution, users should accept to open internal doors. This requirement may lead to privacy problems and is a major limitation of the simplified SH distribution. The increase of set-point temperatures above 21°C leads to higher SH needs, which should theoretically be considered as a type of SH emission losses. This first scenario complies with standards as they compare the energy use of different SH systems for a uniform set-point temperature in all rooms.

2. Secondly, users are satisfied with the lower temperature in rooms not equipped with radiator. This situation may arise when users want lower temperatures in specific rooms. Recent studies have indeed confirmed that many Norwegians desire lower temperatures in bedrooms, typically ~16°C or below (M. Berge & Mathisen, 2016; Magnar Berge et al., 2016; Georges, et al., 2016). People that would like colder bedrooms should typically keep internal doors closed. The set-point temperature for radiators is kept at 21°C only in the basement, the living room and the corridor of the first floor, for both the simplified and the standard loops (i.e. the thermostatic valve in other rooms are fully closed). In this second scenario, the increase of temperature due to pipe losses in non-heated zones is assumed to have no value.

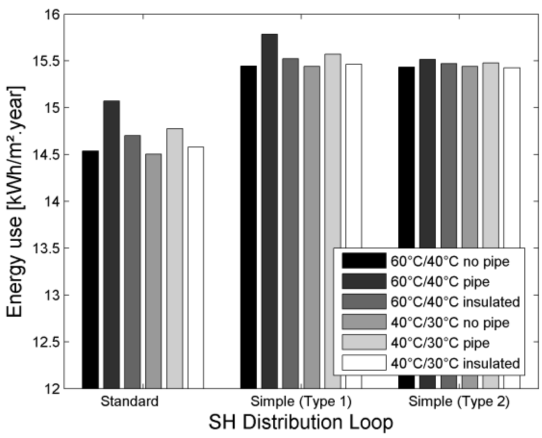

Figure 6. Energy use (Q_d) for the different loops with a minimum temperature of 21°C in each room (with open internal doors).

Both scenarios have been simulated in IDA-ICE for the three types of loops. Other possible scenarios can be seen as intermediate cases between these two extreme scenarios. The scenario (1) of a minimum temperature of 21°C in each room is shown in Figure 6. Starting with the idealized case without pipe losses, the simplified loops need a higher temperature in the rooms equipped with radiator (see e.g. Figure 6) leading to a higher energy use by ~1 kWh. Again, it translates a loss of emission efficiency. Taking pipe losses into account, the higher distribution efficiency (η_d) of simplified loops does not compensate for the initial increase of ~1 kWh (due to emission efficiency). For instance, the standard loop at 60°C/40°C without insulation has an energy use of 15.1 kWh/m².year while the equivalent simplified loop (Type 2) uses 15.5 kWh/m².year. The simplified distribution is thus less energy-efficient than the standard distribution.

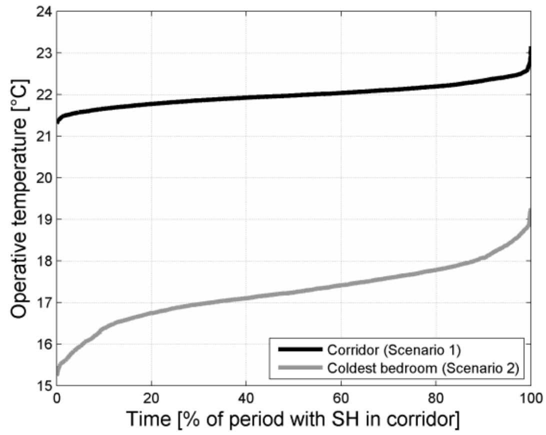

Figure 7. Duration curve of the corridor temperature in the first floor using scenario 1 and the double bedroom temperature in scenario 2 (case with 60°C/40°C distribution without insulation).

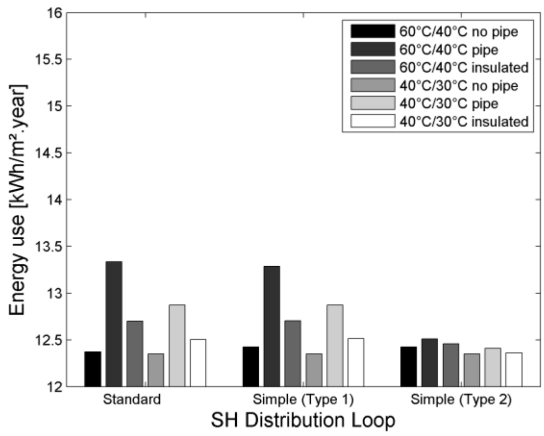

Figure 8. Energy use (Q_d) for different loops with a temperature of 21°C only imposed in the basement, living room and hall (with closed internal doors).

The scenario (2) with a set-point temperature of 21°C only applied in the basement, living room and corridor of the first floor, is shown in Figure 8. Starting with cases without pipe losses, the energy delivered to the distribution system (Q_d) is equal for each case. The temperature zoning (i.e. lower temperature in bedrooms such as in Figure 7) reduces the yearly energy to ~2 kWh compared to the previous scenario (1). Including pipes losses, results for the three distribution layouts are mixed. The simplified loop with pipes crossing non-heated zones (Type 1) does not outperform the standard loop. In fact, the fraction of losses (ξ) is comparable for both cases. The simplified loop has fewer pipes but with higher mass flows than the standard loop. On the contrary, the simplified loop with pipes only crossing heated zones (Type 2) always has higher distribution efficiency leading to yearly energy uses 0.25 to 1 kWh lower than the standard loop.

Discussion

Both temperature levels (60°C/40°C and 40°C/30°C) are used in practice, but pipe insulation inside the building protected volume is almost never applied. In this context, it can be concluded that the energy performance of the standard loop compared to the simplified loop (Type 2) depends on the desired temperature differences between rooms (e.g. desire for cold bedrooms or not), with a difference of 0.5-1.0 kWh between both scenarios. These variations are non negligible for super-insulated buildings with SH needs of ~15 kWh/m².year. Nevertheless, they are small compared to the influence of users over the SH energy use, for instance by adjusting the set-point SH temperature, by opening the windows frequently during winter time, or the user influence over the domestic hot water (DHW) needs (Dar et al., 2015; Georges, et al., 2016). For these cases, variations higher than ~5 kWh/m².year are frequently reported. In general, it is well known that users have relatively more influence over the energy use for heating when the building is more insulated. It can then be concluded that the question of the SH distribution efficiency is secondary. This confirms that the first reason for simplification of the SH distribution is the reduction of investment costs (Feist, et al., 2005). To the authors 'opinion, the reduction in embodied energy and CO_{2eq} emissions from a lifecycle perspective (LCA) resulting from the reduced amount of pipes and radiators has not been investigated yet in the scientific literature.

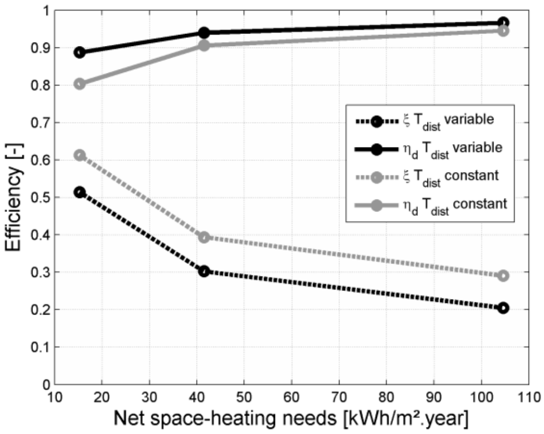

Figure 9. Yearly performance of the 60°C/40°C standard distribution loop without pipe insulation for the three buildings, with and without weather-compensated heating curve (with internal doors closed).

Present investigations applied state-of-the-art control techniques, meaning a weather-compensated heating curve and a shutdown of the SH distribution outside the heating season. Due to higher shares of losses (ξ), super-insulated buildings are more vulnerable to distribution losses if these control techniques are not applied, or if pipes are located outside the heated volume. Example is given in Figures 9 and 10 for a constant distribution temperature (T_{dist}) compared to a weather-compensated distribution temperature. Figure 9 shows that the fraction of losses (ξ) increases by ~10% for each insulation level. While it only decreases the yearly distribution efficiency (η_d) by 2% for the TEK87 house, it decreases this efficiency by 10% for the PH case. Figure 10 only focuses on the PH case and shows how the monthly η_d is lower during the shoulder months of the SH season. These months are characterized by lower SH needs so that the utilization factor of internal gains is lower (CEN, 2008a).

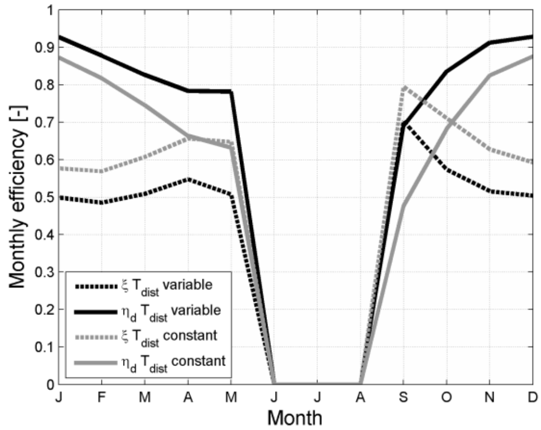

Figure 10. Monthly performance of the 60°C/40°C standard distribution loop in the PH without pipe insulation, with and without weather-compensated heating curve (with internal doors closed).

A limitation of the present study is the constant heat transfer coefficient of pipes U_w. The thermal inertia of pipes is also not accounted for. This is inherent to the current implementation of the pipe model available in IDA-ICE. This is nonetheless not specific to IDA-ICE. For instance, the pipe model of TRNSYS (*Type 31*) also presents a same limitation (Klein et al., 2010). These models should be extended to variable U_w and include thermal inertia. Finally, the thermostatic valve control has been assumed perfect.

Conclusion

To date, the energy efficiency of hydronic SH distribution in super-insulated buildings has not been investigated in detail. Compared to less insulated buildings, the fraction of losses from the SH distribution system (ξ) is expected to increase significantly. Nevertheless, super-insulated building envelopes are better heat storages, so that the utilization factor of internal gains is higher. The resulting energy efficiency of the SH distribution is unknown. In addition, simplifying the SH distribution could be an option to reduce these losses, essentially by reducing the piping length.

Detailed dynamic simulations (here using IDA-ICE) are ideal to investigate this problem as instantaneous mass flow and temperature of pipes are evaluated at each time step, but it requires the detailed modeling of the SH distribution network. By default, this detailed modeling is not implemented in building simulation packages where simplified approaches are rather proposed.

Simulations showed that uncontrolled thermal losses from pipes can cover up to ~50% of the annual SH energy use (i.e. ξ < 50%). Nevertheless, the study showed that the super-insulated building can recover most of these losses usefully, and keep the distribution efficiency (η_d) above ~90%, for all the distribution loops investigated. In super-insulated buildings, high ξ would advocate that the SH distribution system should be properly taken into account during design and modelled in detail. It is a “false alert”, the present study suggests on the contrary that the error is limited if the SH distribution system is not analysed in detail (as η_d remains high). This is also an important conclusion for developers of BPS softwares.

The simplified distribution system showed better distribution efficiency (η_d) than the standard distribution loop. It is especially true if the distribution pipes of the simplified loop cross heated zones only. Then the η_d is almost perfect (~99%). Nevertheless, for users that would like a same temperature in all rooms, the set-point temperature in rooms equipped with radiator should be increased to ensure the minimal temperature in rooms without heat emitter. This effect can be considered as SH emission losses. Simulations show that the resulting increase in SH energy use would prevail over the improved η_d using simplified SH distribution. In the end, the relative energy performance between the simplified and standard SH distribution systems depends on the desired temperature differences between rooms (e.g. desire for cold bedrooms or not). The computed differences in annual energy use have been here evaluated to be between 0.5-1.0 kWh/year. These differences are not negligible for super-insulated building (with typical SH needs of ~15 kWh/m².year). Nevertheless, these numbers are small compared to variations in energy use generated by occupant behavior, such as a change of the indoor set-point temperature, frequent opening of windows during the SH season or the variability of DHW energy use. Consequently, present investigations suggest that the energy efficiency of SH distribution system in super-insulated buildings is a secondary problem (if the SH distribution temperature is controlled in a proper way). The main motivation for the simplification of SH distribution system thus remains the reduction of investment costs.

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