ANALYSIS OF THE AIR HEATING IN NORWEGIAN PASSIVE HOUSES USING DETAILED DYNAMIC SIMULATIONS

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ABSTRACT

The passive house (PH) standard is seen as the future minimal requirement for buildings in Norway, where a specific definition has been developed (NS 3700). Nevertheless, the relation between this standard and air heating (AH) is not clear while both concepts are often associated. The present contribution investigates challenges for AH in terms of thermal dynamics (e.g. temperature distribution and control) as well as the feasibility of the AH concept. This is done using detailed dynamic simulations on a typical detached house typology. Results show some limitations of the AH concept in Nordic countries, as well as provide guidelines for the design procedure.

INTRODUCTION

The passive house (PH) is a standard that aims at promoting energy efficiency. The main concept of the passive house is based on reduction of the space-heating (SH) needs using a super-insulated envelope. In the original philosophy of the passive house (Feist 2005), the minimal requirement for the envelope performance has been strongly connected to the air-heating (AH) concept. In practice, the building envelope should be sufficiently insulated so that it is possible to cover the SH by the ventilation air at standard hygienic flow rates. Another underlying assumption is that the maximal inlet AH temperature can be raised up to 50-55°C, representative of the temperature of dust carbonization. A direct consequence of the AH concept is that the passive house should resort to high performance windows (e.g. using triple glazing) in order to prevent excessive cold draft or discomfort induced by an internal cold surface.

A specific definition of the PH standard has been defined for Norway, the NS 3700 (Standard Norge 2010). Although not official yet, this standard is often considered as the future legal requirement for new buildings after 2015, while it is also seen as the minimal envelope performance for future Norwegian net-Zero Emission Buildings (nZEB). Although these objectives are ambitious and at a short term, there is still a lack of experience about AH in Norwegian PH so that this knowledge should be quickly gained. Paradoxically, the NS 3700 is not based on the AH concept although it is explicitly written that it derives the German PH concept to Norway. Therefore, the present contribution investigates the AH potential in a Nordic context, characterized by large differences between climate zones as well as low solar angles. Accordingly, our work takes as a basis assumption that the maximal AH temperature is 55°C, mixing ventilation and that flow rates can only be increased up to ~50% above the nominal rates, based on hygienic considerations, at peak load.

A broad review of the questions regarding the indoor air quality (IAQ) in passive houses can be found in (Thomsen 2012). Investigations on AH specific to Nordic climates are mostly based on Swedish works (Karlsson 2006; Wall 2006; Isaksson 2011; Molin 2011). In terms of thermal comfort and energy efficiency only, we propose to classify the challenges for the AH of passive houses in the following way:

1. **Design and robustness of the AH concept**. Given the different climate zones in Norway, is the maximal AH power actually enough to cover the SH load during all the winter? What are the boundary conditions for the AH design (e.g. outdoor temperature and solar irradiation)?
2. **Air distribution inside a room**. Using AH, the flow is buoyancy driven by the cold draft of windows and by the plumes generated by internal heat loads (Krajčík 2012). In practice, there is still a risk of strong temperature stratification or potentially uncomfortable draft. Furthermore, reduced ventilation effectiveness can be found, e.g. the fresh air shortcuts to the exhaust Air Terminal Device, ATD (Mathisen 1989). These phenomena are also dependent on the room geometry, AH temperature and ATDs locations. Although, dedicated research is still needed, recent works based on measurements (Feist 2005; Krajčík 2012) did not report any severe issue: these results investigated AH temperatures up to ~45°C.
3. **Distribution losses in ventilation ducts**. Thermal losses from ducts are significant and may affect the thermal comfort in passive houses. Losses should be a part of the design and can also be used to improve the thermal comfort in specific rooms (e.g. bathrooms) (Feist 2005).
4. **AH thermal dynamics**. Assuming a single heating coil for a centralized AH, there is a non-

uniform distribution of temperature between rooms. This distribution is mainly influenced by the building architectonic properties, the climate and the AH control. In addition, it is also worth investigating the influence of a complementary SH emission in bathrooms, the effect of the internal gains distribution inside the building, the influence of the solar gains (e.g. shading strategy), and the influence of opening the doors inside the building.

5. **Maximal AH temperature**. Is the characteristic temperature before dust carbonization the correct criterion for thermal comfort and IAQ?

Even though all these five questions deserve a proper treatment, the present article specifically focuses on points (1) and (4). In parallel, an idealized behaviour for questions (2) and (3) is assumed (i.e. a perfect mixing and no distribution losses, respectively). In this context, investigations are consistently performed using detailed dynamic simulations, here applied to one benchmark Norwegian passive house. A sensitivity analysis is done using a set of ~700 simulations with a time step of 1 min. Only most representative results are reported in the paper.

SIMULATION PROCEDURE

Building model

Given these assumptions, investigations are performed using detailed dynamic simulations, here using TRNSYS (Klein et al. 2010). The multi-zone building model, Type 56, is applied where each zone is consistently represented by one air-node (i.e. perfect mixing). In order to investigate natural convection inside the envelope, the airflow rates between rooms are computed using a ventilation-network model, here TRNFLOW based on the COMIS library. Feist et al. (Feist 2005) indeed demonstrated that the opening of the internal doors is an efficient way to homogenize the temperature within the envelope. Doors are modelled using a large opening approximation (Etheridge 1996) introducing a discharge coefficient, C_d, to tune the model to a specific flow physics. Measurements have shown that C_d for doors typically ranges between 0.4 and 0.8 (Heiselberg 2006), while a default value of 0.65 is here applied. Doors have a section of 1m x 2.1m, with a 1cm opening underneath when closed. Finally, the thermal comfort is evaluated globally using the operative temperature, T_{op} (CEN 2005).

Benchmark passive house

A same detached single-family house geometry is used as a benchmark building for all simulations. It is a typical two-storey's building extracted from a house manufacturer catalogue (Mesterhus 2012), a common typology in Norway. The house has a net heated surface (A_{fl}) of 173.5 m^2. The house and its internal organization are shown in Fig. 1: the building is divided into 8 thermal zones. The living room faces the south. It is assumed that the house is placed on a flat and open terrain without obstacles.

The building has balanced mechanical ventilation equipped with a heat recovery unit. The constant-air-volume (CAV) ventilation operates a cascade-flow: the fresh air is supplied in the living rooms and bedrooms, and is extracted in *wet rooms* (e.g. bathroom). Standard hygienic flow rates (V_n) are imposed, with a mean fresh airflow rate of 1.2 $m^3/m^2.h$ (KRD 2010). As mentioned, it is assumed that the airflow rate can only be boosted up to 50% above V_n. By default, time-constant and space-uniform internal gains with a value of 4.2 W/m^2 comparable to the NS 3700 are applied to the building model, while 2.1 W/m^2 is considered in the PHPP tool (Feist 2007) used for the design of German PH.

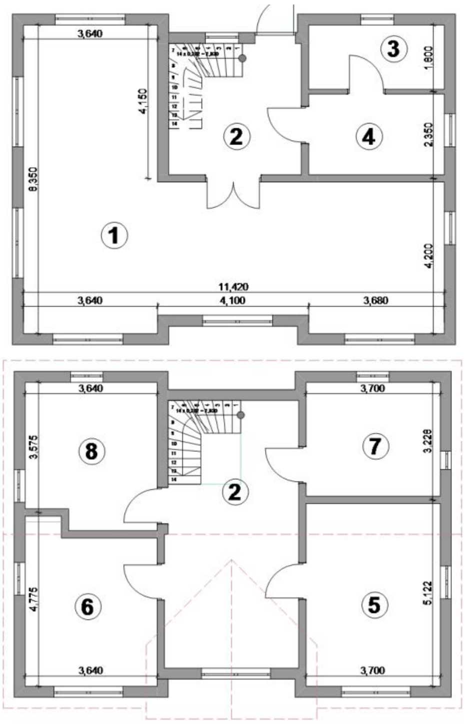

Figure 1 Sketches of the first and second floors: kitchen coupled to the living room (zone1), corridor with an open staircase towards the second floor (zone2), technical room (zone 3), bathrooms (zones 4 and 7) and bedrooms (zones 5,6,8).

Table 1 Weather characteristics for the 3 locations: $I_{tot,rad}$ is the mean total radiation on a horizontal surface, $\theta_{SH,dim}$ is the SH design outdoor temperature.

	Θ_{ym} [°C]	$I_{tot,rad}$ [W/m²]	$\Theta_{SH,dim}$ [°C]	Q_{max}* [kWh/m².y]
Oslo	6.3	110	-20.0	19.2
Bergen	7.5	87	-11.7	19.1
Karasjok	-2.5	79	-48.0	41.6

*Given in NS 3700, depending on θ_{ym} and A_{fl} only

Table 2 Building envelope performance as a function of the geographic location: U-value of external walls ($U_{ext,wall}$), the roof (U_{roof}), the slab (U_{slab}) and the windows (U_{win}); normalized thermal bridges (ψ"), efficiency of the heat recovery (η_{exch}), infiltration rate at 50 Pa (n_{50}) as well as net SH needs computed using SIMIEN (Q_{net}) and maximum net SH power (P_{SH}) with a constant set-point temperature.

	$U_{ext,wall}$ [W/m².K]	U_{roof} [W/m².K]	U_{slab} [W/m².K]	U_{win} [W/m².K]	Ψ" [W/m².K]	η_{exch} [%]	n_{50} [1/h]	Q_{net} [kWh/m².y]	P_{SH} [W/m²]
Oslo	0.15	0.12	0.11	0.72	0.03	85	0.6	18.9	16.6
Bergen	0.15	0.16	0.11	0.80	0.03	85	0.6	16.0	11.7
Karasjok	0.12	0.09	0.08	0.72	0.03	85	0.6	41.0	26.3
NS 3700*	0.15	0.13	0.15	0.80	0.03	80	0.6	-	-

**Minimal requirement by building component imposed by the Norwegian PH standard, NS 3700*

Table 3 Building construction modes: overall building inertia using EN 13790, U-value of floor/ceiling (U_{floor}), partition walls (U_{part}) and bearing walls ($U_{bearing}$).

CONSTRUCTION TYPE	INERTIA TYPE	INERTIA [MJ/K]	U_{floor} [W/m².K]	U_{part} [W/m².K]	$U_{bearing}$ [W/m².K]
Masonry heavy	*Very-heavy*	86	1.6	3.2	2.8
Mixed wood-masonry	*Heavy*	41	1.6	0.33	2.8
Wooden heavy	*Medium*	35	0.23	0.33	2.8
Masonry light	*Light*	26	0.21	0.33	1.1
Wooden light	*Very-Light*	14	0.21	0.33	0.25

Construction modes

The NS 3700 defines a minimal performance requirement for each building component (e.g. external walls, windows) as well as a maximum value admitted for the annual net SH needs (Q_{max}). This last criterion is made dependent on the local weather conditions and the building compactness: Q_{max} is adapted as a f unction of the annual mean outdoor temperature (θ_{ym}) and the heated area (A_{fl}). Three different building locations are considered here, see Table 1: Oslo, Bergen and Karasjok. Although limited, this set of locations enables a coarse estimate of the wide range of weather conditions found in Norway. The SH set-point temperature (T_{set}) is fixed at 21°C by the NS 3700.

The building envelope performance has been defined to comply with the NS 3700. This has been verified using the software SIMIEN (ProgramByggerne) equipped with s pecific modules to check the compliance with building standards. As three locations are considered, three levels of building envelope performance are defined (see Table 2).

Furthermore, different construction modes may lead to the same envelope performance (e.g. using masonry or wood). Five possible construction modes that correspond to five different level of internal thermal mass have been defined using Norwegian technical literature (Byggforsk), see Table 3. They range from *very-heavy* to *very-light* according to EN 13790 (CEN 2008). In practice, the different construction modes have different levels of thermal insulation located inside the building envelope (e.g. in partition walls between rooms). This insulation is essentially placed for acoustic reasons. In general, one notices that the higher the thermal mass, the lower the insulation level in internal walls. Finally, it is worth mentioning that wooden constructions are commonly used in Norway.

Air heating modelling

The AH temperature (T_{AH}) is adapted to enforce one reference temperature at T_{set}. By default, the air temperature in the living room is here used. Another common strategy is to resort to the mean return temperature of the ventilation air ($T_{vent,r}$), an alternative that is also tested. The power to raise the ventilation inlet temperature (T_{in}) for the AH is controlled using a PI action (requiring to apply a time step of 1 min for simulations). For the sake of clarity, a constant T_{set} is only considered here. The question of the extra-power for an intermittent SH will in fact lead to higher T_{AH} (e.g. when using a night setback).

PERFORMANCE IN STD

AH performance is here analyzed in Standard Design Conditions (STD): it assumes steady-state conditions with the $\theta_{SH,dim}$ introduced in Table 1 and the building without solar gains.

Maximal AH temperature during STD

Assuming a **mono-zone** building, a simple **analytical** approach can be formulated. Knowing the heating power (P_{SH}) from the passive house assessment using SIMIEN (see Table 2), the resulting T_{AH} in STD can be evaluated using the simple formula:

$$P_{SH} = \alpha\, V_n C_p\, (T_{AH} - T_{in}), \quad (1)$$

$$T_{in} = \eta_{exch}\, (T_{set} - \theta_{SH,dim}) + \theta_{SH,dim}, \quad (2)$$

$$\alpha = V / V_n, \quad (3)$$

where V is the forced/actual airflow rate.

Table 4 Possibility to implement AH and corresponding T_{AH}: comparison between the ***analytical mono-zone*** *and* ***multi-zone*** *methods in* ***STD*** *as well as the* ***multi-zone*** *model during a* ***TMY*** *(using closed internal doors).*

BUILDING MODEL			MONO-ZONE		MULTI-ZONE		MULTI-ZONE		
OPERATING CONDITIONS			**STD**		**STD**		**TMY**		
V	**GAINS [W/m²]**	**CLIMATE**		**T_{AH} [°C]**		**T_{AH} [°C]**		**$T_{AH,max}$ [°C]**	**$T_{AH,95\%}$ [°C]**
V_n	0.0	Oslo	KO	-	KO	-	Limit	[51.1;55.0]	[46.5;52.3]
		Bergen	KO	-	KO	-	OK	[45.6;50.6]	[42.0;45.9]
		Karasjok	KO	-	KO	-	KO	-	-
	4.2	Oslo	Limit	55.6	Limit	[49.5;55.0]	OK	[41.2;48.7]	[36.7;41.4]
		Bergen	OK	44.9	OK	[42.7;47.1]	OK	[35.8;40.0]	[32.6;35.3]
		Karasjok	KO	-	KO	-	KO	-	-
3/2 V_n	0.0	Oslo	OK	48.9	OK	[45.9;50.5]	OK	[40.4;45.6]	[37.6;41.1]
		Bergen	OK	43.2	OK	[41.2;44.6]	OK	[37.0;40.1]	[34.8;37.2]
		Karasjok	KO	-	KO	-	OK	[48.0;52.9]	[45.7;49.2]
	4.2	Oslo	OK	42.0	OK	[40.0;44.0]	OK	[34.0;38.7]	[31.3;34.3]
		Bergen	OK	35.4	OK	[35.3;38.0]	OK	[30.7;33.3]	[28.6;30.2]
		Karasjok	Limit	53.6	Limit	[49.9;55.0]	OK	[45.1;49.8]	[38.7;44.1]

"OK" when AH possible, "KO" when AH impossible and "Limit" when dependent on construction mode.

Table 5 Temperature distribution during ***STD*** *using the multi-zone building model: maximal and minimal operative temperature, $T_{op,max}$ and $T_{op,min}$, respectively, for all the construction modes*.*

INTERNAL DOORS			CLOSED		OPEN		CLOSED	
SH IN BATHROOMS			**NO**		**NO**		**YES**	
V	**GAINS [W/m²]**	**CLIMATE**	**$T_{op,max}$ [°C]**	**$T_{op,min}$ [°C]**	**$T_{op,max}$ [°C]**	**$T_{op,min}$ [°C]**	**$T_{op,max}$ [°C]**	**$T_{op,min}$ [°C]**
V_n	4.2	Oslo	[23.7;31.3]	[17.5;19.9]	[21.8;22.7]	[19.7;19.9]	[23.8;31.3]	[19.3;20.5]
		Bergen	[22.9;28.8]	[18.2;20.1]	[21.6;22.3]	[19.9;20.1]	[22.9;28.8]	[20.1;20.2]
3/2 V_n	0.0	Oslo	[23.9;31.3]	[17.1;19.8]	[21.9;22.8]	[19.5;19.7]	[24.0;31.3]	[19.9;20.0]
		Bergen	[23.2;30.3]	[17.1;20.0]	[21.7;22.5]	[19.6;19.9]	[23.3;28.8]	[20.0;20.1]
	4.2	Oslo	[23.2;29.2]	[16.8;19.4]	[21.7;22.5]	[19.7;19.9]	[23.3;29.2]	[19.9;20.0]
		Bergen	[22.5;26.7]	[18.9;19.6]	[21.5;22.1]	[19.9;20.1]	[22.6;26.7]	[20.1;20.2]
		Karasjok	[25.2;34.1]	[17.7;19.6]	[22.3;23.4]	[19.4;19.5]	[25.2;34.1]	[18.4;19.6]

**As all the construction modes are considered, the range of values spanned by them are putted into brackets*

The T_{AH} can also be evaluated numerically using the TRNSYS **multi-zone** building model. Comparison between methods is reported on Table 4 and leads to the following conclusions:

- For the multi-zone simulations, T_{AH} is ranging from a few degrees depending on the construction mode considered. This is due to different temperature distributions inside the building giving rise to different thermal losses.
- The T_{AH} using the mono-zone design approach is close to the multi-zone results. In fact, if the mono-zone approach concludes that the AH is impossible, the same conclusion is found using the multi-zone approach.
- In practice, the AH is only possible in Oslo if the ventilation rate is forced to 50% but with a high T_{AH} of approximately 45°C. The climate of Bergen is milder so that AH is possible using V_n at the condition that the 4.2 W/m² internal gains are applied. T_{AH} are then more acceptable and can be limited to about 40°C if the ventilation is forced at 50%. On the contrary, the Karasjok climate is extremely cold. Even though the performance requirements of NS 3700 are adapted to the local climate, the AH is almost impossible during wintertime.

Temperature distribution during STD

Using the multi-zone building model, it is also possible to investigate the temperature distribution within the passive house during STD. Typical results, reported on Table 5, can be summarized in the following way:

- With closed internal doors, large temperature differences take place in the building. Zones with the highest temperature ($T_{op,max}$) are bedrooms while the lowest temperatures ($T_{op,min}$) are found in the bathrooms (without SH). These differences are again dependent on the construction mode: constructions with a low thermal mass are here characterized by a higher thermal insulation in partition walls, so that the temperature difference between zones is increased.
- The colder the climate, the larger the temperature differences inside the building. This

is a direct consequence of higher T_{AH} applied with colder conditions. Accordingly, a same effect is found with internal gains where lower gains lead to higher temperature differences in the building.

- The opening of the internal doors is an efficient way to homogenize heat inside the building. Therefore, difference in temperature distribution between construction modes is reduced (because the thermal conduction through walls is less dominant). Nevertheless, highest temperatures are still found in the bedrooms (typically ~22°C).
- Applying a SH at the same T_{set} in bathrooms significantly reduces $T_{op,min}$ and, thus, improves the thermal comfort. Nevertheless, it does not affect significantly $T_{op,max}$ found in the building.
- From a practical point of view, the AH generates high temperatures in bedrooms while it is known that users may require lower temperatures during the night. A SH night setback does not solve the problem as building characteristic time scales of PH are large (i.e. the temperature does not have the time to decrease significantly during one night). Furthermore, the temperature may even be prohibitive if internal doors are closed and a light building structure is considered. Even for the milder climate of Bergen, it is already the case.

By default, the living room was taken as the reference temperature for the AH control. Another common strategy is to use the mean return temperature of the ventilation air ($T_{vent,r}$). For a same T_{set}, this strategy essentially generates higher building temperatures: the mean zone temperature in the building is increased of about ~3°C. It can be easily understood as $T_{vent,r}$ is mainly based on the wet rooms temperatures (e.g. bathrooms) which always present the lowest temperature when using AH. In fact, the temperature difference between rooms is almost unchanged between the two control strategies. As a consequence, this change of reference temperature for the control can essentially be considered as a shift in the mean building temperature.

PERFORMANCE DURING TMY

Comparison against STD

An interesting question is to check how standard design conditions (STD) are representative of everyday operating conditions. Furthermore, it should also be confirmed that these STD are representative of the most severe operating conditions. According to (Feist 2005), the maximum heating power should be evaluated for two extreme cases. The first case is a cold day with a clear sky and, thus, solar gains. The second case is a milder day with overcast sky (i.e. with negligible solar gains). This procedure is translated in the PHPP evaluation tool (Feist 2007) used in many countries (e.g. Germany). In our case, STD correspond to the design outdoor temperature $\theta_{SH,dim}$ without solar gains.

In order to investigate this, yearly simulations are performed using a Typical Meteorological Year (TMY) (here generated using Meteonorm). In the following considerations, no solar shading strategy is applied during the heating period while internal gains are strictly constant and uniform.

Firstly, the maximal and 95% percentile T_{AH} are reported on Table 4 (termed $T_{AH,max}$ and $T_{AH,95\%}$, respectively). These temperatures are lower than values obtained using STD conditions. It somehow shows that STD conditions are severe when evaluating the maximal T_{AH}: in practice, some cases that were critical in STD (i.e. T_{AH} close to 55°C) present acceptable temperature in STD.

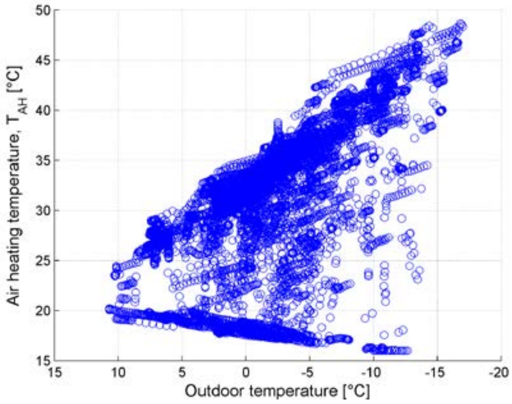

*Figure 2 T_{AH} as a function of the outdoor temperature during a **TMY** for the very-light building located in Oslo (with closed internal doors, constant gains and hygienic ventilation flow rates).*

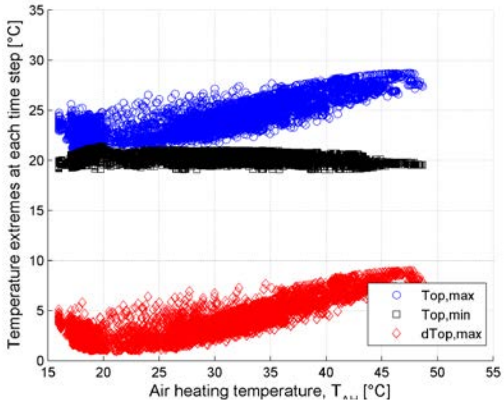

*Figure 3 $T_{op,min}$, $T_{op,max}$ and $dT_{op,max}$ as a function of T_{AH} during a **TMY** for the very-light building located in Oslo (with closed internal doors, constant gains and hygienic ventilation flow rates).*

Secondly, hourly $T_{op,max}$ and $T_{op,min}$ can be analyzed during a TMY along with the maximal temperature difference in the building, $dT_{op,max}$. In Figs. 2 and 3, results are presented for the very-light building located in Oslo, using hygienic ventilation airflow rates (i.e. $V = V_n$) as well as closed internal doors. A similar behaviour was found for all other test cases.

From Fig. 2, one clearly notices that the maximal T_{AH} is found during the coldest day. Furthermore, Fig. 3 also shows that the temperature differences in the building are mainly driven by the T_{AH}, the trend is indeed almost linear. It confirms that STD conditions make sense in the AH design. In other words, one should not expect more severe operating conditions than considering the STD. Finally, rooms that were identified to be the warmer and colder in STD are the same when using a TMY. The aforementioned conclusions are even more obvious for the climate of Karasjok where the wintertime is characterized by the absence of sun.

Influence of the internal gains resolution

As only one temperature is used to control the centralized heating coil, one may suspect that the distribution of the internal gains may generate configurations between zones that are less favourable in terms of thermal comfort. Furthermore, internal gains are not constant so that period with lower gains may occur.

At this stage, only time-constant and space-uniform internal gains were introduced in the building model. Two alternative gains profiles are now introduced:

- First, the internal gains of the **NS 3700** are applied strictly. These are also space-uniform but using different levels during the day and night periods: the night is then characterized by lower internal gains from lighting and equipments.
- Second, synthetic time- and space-varying internal gains are applied (with 1-hour resolution). These **synthetic** gains have been generated in a way that (a) they have a mean value of 4.2 W/m² as the NS 3700, (b) the yearly energy consumption of electric appliances is compatible with measurements (Enertech 2008; Sæle 2010) (also using typical operating cycle lengths), (c) as well as daily profiles consistent with a Norwegian time-of-use survey (Holmøy 2012). The location of the different electric appliances has been allocated in a meaningful way according to building spatial organization, see Fig. 1. Mean value of the synthetic internal gains in the living room is 6.1 W/m², a value of ~4 W/m² is applied to bedrooms while < 1.0 W/m² in bathrooms.

Results using the different gains are reports on Tables 6 to 8 for the Oslo climate. Comparing performance using the constant and NS 3700 gains, one clearly notices than the maximal T_{AH} increases significantly: this is due to lower gains during the night. The temperature distribution in the building does not change noticeably and is only a result of the increase in T_{AH}.

*Table 6 Thermal comfort during a **TMY** for the Oslo climate with **constant gains, no shading** (with closed doors and hygienic ventilation flow rates).*

CONSTR. MODE	$T_{op,g,max}$ [°C]	$T_{op,g,min}$ [°C]	$T_{AH,max}$ [°C]
Very-heavy	22.4	20.0	41.2
Heavy	23.6	18.3	42.6
Medium	25.5	19.0	42.8
Light	26.1	18.9	45.7
Very-light	27.6	19.0	48.6

*Table 7 Thermal comfort during a **TMY** for the Oslo climate with **NS 3700 gains, no shading** (with closed doors and hygienic ventilation flow rates).*

CONSTR. MODE	$T_{op,g,max}$ [°C]	$T_{op,g,min}$ [°C]	$T_{AH,max}$ [°C]
Very-heavy	22.6	19.9	45.8
Heavy	24.1	18.0	47.6
Medium	26.1	18.9	48.2
Light	26.8	18.8	51.6
Very-light	28.3	19.0	55.0

*Table 8 Thermal comfort during a **TMY** for the Oslo climate with **synthetic gains, no shading** (with closed doors and hygienic ventilation flow rates).*

CONSTR. MODE	$T_{op,g,max}$ [°C]	$T_{op,g,min}$ [°C]	$T_{AH,max}$ [°C]
Very-heavy	22.8	18.8	49.3
Heavy	25.6	16.5	51.2
Medium	27.1	16.9	52.4
Light	27.6	16.3	54.6
Very-light	28.6	15.9	55.0

The synthetic gains present the largest variability in space and time. As a result, the maximal T_{AH} found are even higher than using the NS 3700 gains. This increase also leads to a slight rise of the maximal building temperature ($T_{op,g,max}$). On the contrary, the minimal temperature ($T_{op,g,min}$) is strongly affected by the synthetic gains: a different temperature distribution in the building occurs due to different gains levels applied in the different rooms (e.g. lower in bathrooms). It is worth noticing than the $T_{AH,max}$ with variables gains are bounded with TMY values obtained with 0.0 and 4.2 W/m² constant gains (see Table 4). It is the same with $T_{op,g,max}$ but not for the $T_{op,g,min}$: this temperature is dependent on the space distribution of internal gains.

Influence of the shading strategy

The same analysis has been carried out for the solar gains and the solar shading strategy. Again, results up to now were obtained without solar shading. Since, low solar altitudes characterize Nordic climates, users commonly use shading to prevent glare. To investigate this effect, an external blind is applied at each window and is closed when the solar radiation on the corresponding façade is higher than 140 W/m². When closed, shading factor is equal to 0.9. Results are reported in Table 9 and should be compared to Table 7. This shading strategy is quite effective: for Oslo, it increases the net SH needs from [16.2;18.3] to [20.9;23.1] kWh/m².an.

*Table 9 Thermal comfort during a **TMY** for the Oslo climate with **NS 3700 gains, with shading** (with closed doors and hygienic ventilation flow rates).*

CONSTR. MODE	$T_{op,g,max}$ [°C]	$T_{op,g,min}$ [°C]	$T_{AH,max}$ [°C]
Very-heavy	22.9	20.1	46.3
Heavy	24.1	18.2	47.6
Medium	26.4	19.1	47.9
Light	28.3	19.5	51.2
Very-light	28.6	20.0	55.0

The shading does not reduce the overheating. It translates the fact that, in wintertime, solar gains do not significantly contribute to the temperature distribution. It is related to results found in Figs. 2 and 3. In fact, an extended analysis (not reported here) shows that the temperature difference tends to increase sensibly with the solar shading. These investigations suggest that an extended analysis of the shading influence is not required for the AH design. Nevertheless, a larger set of shading configurations should also be tested in order to rigorously confirm this last conclusion.

CONCLUSION

This work investigates air heating (AH) utilized as space heating (SH) of Norwegian passive houses (PH); these houses being characterized by a specific Norwegian standard (i.e. the NS 3700). Although this standard is considered as the future minimal requirements for buildings in the coming years, there is still a lack of experience about AH in Norwegian PH. This paper first presents a list a challenges for the AH, and proposes to investigate questions related to the system thermal dynamics as well as the possibility to apply AH from a conceptual point of view. This is done using detailed dynamic simulations (here TRNSYS) on a typical detached house typology. The AH is here based on one centralized heating coil. Its performance is first analyzed for standard design conditions (STD), defined by an outdoor SH design temperature and no solar gains, and subsequently using a Typical Meteorological Year (TMY). Results, based on a set of ~700 distinct simulations, lead to the following conclusions in terms of physics and implications in AH design:

- The **maximal value of the AH temperature** ($T_{AH,max}$) can be evaluated analytically using the design SH power computed during the envelope design (P_{SH}) in STD and assuming a mono-zone building. Although very simple, it is an easy and convenient way to screen the AH potential for a specific project (i.e. building type and location).
- In theory, the **maximal value of the AH temperature** ($T_{AH,max}$) should be evaluated in STD without internal gains. This scenario is too conservative and would disqualify the AH approach in too many building projects where the T_{AH} is in fact acceptable during usual operating conditions (here considering a TMY). $T_{AH,max}$ could be better approximated using STD with 4.2 W/m² constant gains. In fact, simulations using a TMY and these gains produce T_{AH} which are still significantly lower. Nevertheless, the analysis of internal gains variability during a TMY showed that higher T_{AH} occur in periods with lower gains. Consequently, $T_{AH,max}$ estimated using STD and 4.2 W/m² constant gains are conservative values but no excessively, as it gives a realistic margin to protect against the effect of the internal gains variability. Furthermore, rather than only using TMY conditions for design, the STD accounts for extreme weather conditions (e.g. the effect of a cold wave).
- The AH based on a centralized heating coil leads to an **uneven temperature distribution** inside the building. A multi-zone building analysis is then required for a proper design. Furthermore, this temperature distribution is strongly related to the building architectonic properties (e.g. level of insulation in internal walls). Furthermore, the spatial distribution of internal gains should be considered to have an accurate assessment of this temperature distribution. Present investigations have not shown a similar effect with solar gains. As a reminder, a multi-zone analysis is also mandatory to properly take into account the influence of heat losses from ventilation ducts.
- STD conditions lead to the most severe **temperature distribution** inside the building. Therefore, the AH design could be limited to these conditions. In fact, investigations using TMY did not show any other critical configurations.
- As regard the **specific building typology investigated** here, the AH does not seem to be well adapted, or, at least, not in this standard form. Firstly, except for milder climates (i.e. Bergen), the T_{AH} are quite high or significantly higher ventilation flow rates are required (i.e. compared to hygienic flow rates). Secondly, even for the milder climate, high temperatures are found in bedrooms, temperatures that are most probably not acceptable for users. Furthermore, the AH control does not give any flexibility for the user to reduce the temperature locally in bedrooms. A possible solution to homogenize heat inside the building envelope is to open the internal doors. Finally, these results suggest that AH should preferably be combined with a peak-load heating system and/or the number of heating coils should be increased.

NOMENCLATURE

A_{fl} = net heated surface
AH = air heating
ATD = air terminal device
C_d = discharge coefficient for doors
η_{exch} = efficiency of the heat recovery unit
n_{50} = infiltration rate at 50 Pa
$I_{tot,rad}$ = mean total radiation on horizontal
PI = proportional-integral control
P_{SH} = maximal net SH power with constant T_{set}
Q_{net} = net SH needs
Q_{max} = maximum net SH needs in NS 3700
Ψ'' = normalized cold bridges
SH = space heating
$\theta_{SH,dim}$ = SH design outdoor temperature
θ_{ym} = annual mean outdoor temperature
STD = standard SH design conditions
T_{AH} = air-heating temperature
$T_{AH,max}$ = maximal T_{AH} during TMY
$T_{AH,95\%}$ = 95% percentile of T_{AH} during TMY
TMY = typical meteorological year
T_{op} = operative temperature
$T_{op,max}$ = instantaneous maximal T_{op} among thermal zones (hourly value)
$T_{op,min}$ = instantaneous minimal T_{op} among thermal zones (hourly value)
$T_{op,g,max}$ = global maximal T_{op} during TMY
$T_{op,g,min}$ = global minimal T_{op} during TMY
$dT_{op,max}$ = instantaneous maximal difference between T_{op} in building (hourly value)
T_{set} = set-point SH temperature
$T_{vent,r}$ = mean return temperature of ventilation air
U = thermal transmittance
V = forced/actual ventilation airflow rate
V_n = nominal ventilation airflow rate

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