4. Design, installation, operation and human behaviour influence on energy consumption of HVAC system

4.1. Introduction

This section of the report will analyse the results of existing researches and case studies on how the design, installation, operation and human behaviour factors can affect the energy consumption of heating, cooling and ventilation systems for nZEB.

As the nZEB must ensure the appropriate indoor climate conditions by consuming minimal amount of energy it is vitally important that starting from the design stage and up to real time operation the system components are selected correctly, built according to the best practise and finally operated as foreseen. Sometimes this can be a difficult task due to the fact that modern buildings can be very complex and have a lot of BMS subsystems which takes highly educated personnel to operate them. Therefore, the best solutions are always the ones that are self-sustainable, failsafe, easy to understand and control and have high level of reliability. However, as the HVAC systems are strictly dependent on many constantly variating factors, like outdoor environment, indoor pollutants and necessary indoor parameters, it is often necessary to install a lot of sensors and control elements to constantly adjust the working parameters of these systems.

The practise shows that in many cases the good intentions of having building with low energy consumption are lost during the building process, when some elements are changed or not installed as stated in the design, or during operation when the responsible persons are not instructed on how to take full advantage of installed technology. Even if everything is built and operated as foreseen, the human factor of buildings everyday users can still play a large role in the final energy consumption of building. Therefore, to ensure that the building will really consume the stated very low amount of energy all the following stages of building life and factors and must be addressed:

1. Design stage;
2. System installation stage;
3. Operation stage
4. Human behaviour factors;

4.2. Design stage

The first step in successful completion of nZEB is to have high quality and integrated design. It means that all the designed systems must serve the specific building acknowledging the location, architectural design, premise usage type, available energy resources, etc. Usually this is the most easily accomplished stage, as it is possible to make everything work on paper. Especially if the customer has sufficient founds and the set goals are high. In such cases it is possible to foresee modern, high-end technical equipment that has high energy efficiency and control systems with all the necessary automation.

During design stage most of the challenges arise in coordination process between various disciplines and to make sure that nothing gets lost in the grey zones. To avoid this, at the start of the design process strict lines of responsibility must be stated. Also if during the design process the building undergoes many frequent and noticeable changes it can complicate the process as the latest information sometimes is not spread to all the members involved. However, if there is sufficient time left for design stage it is possible to perform analysis and energy calculations of various scenarios to find the one most suitable for given building. Such complex energy simulations can be performed in software's like IDA-ICE, IESVE, Energy+, RIUSKA or others. The Figure 4.1 shows the principle scheme of the parameters and their interactions that are most commonly taken into account in these software's.

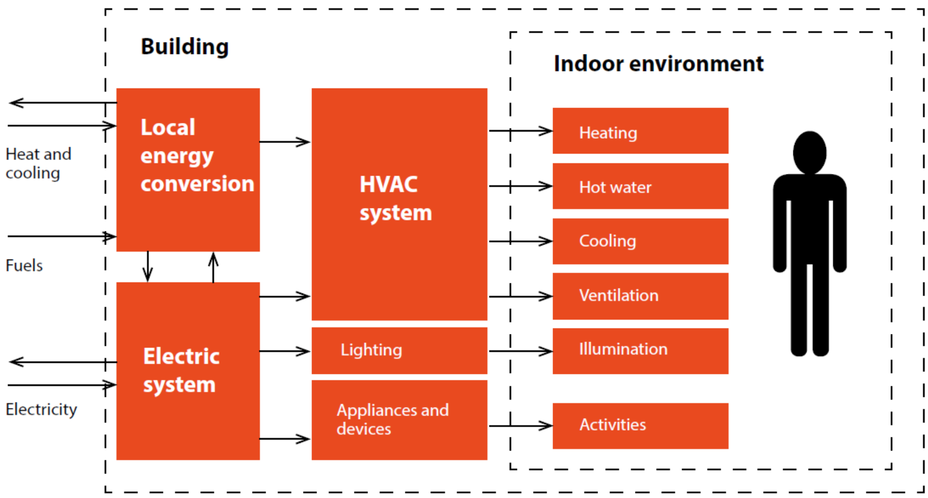

Figure 4.1. *Parameters considered in simulation programs [1]*

4.3. Heating systems

One of the first systems that must be designed for nZEB buildings located in norther climate is heating as every building must have some type of such system and the maximal allowed amount consumed by it is strictly regulated in the standards. The heating system design can be divided in several subtasks:

1) Calculating the necessary design heat load
2) Estimating the annual energy consumption for heating
3) Choosing the heating system type
4) Choosing and designing the heat source
5) Designing and calculating rest of the system elements, like, pipes, insulation, balancing valves, expansion vessels, storage tanks, etc.

The design heat load is the maximal necessary amount of heating energy that is needed to ensure the necessary indoor temperature for the specific building, knowing its external constructions, U-values, outdoor parameters for given location, assuming that there are no internal heat gains. This is needed for sizing of the system elements and does not vary depending on heating source type or the specifics of heating system.

On the other hand, annual heating energy consumption, which actually shows how much energy the building will consume during whole year is dependent on some additional factors, like internal heat gains, solar gains, thermal capacity of building elements, operation time of the systems and occupant behaviour. It can be stated that exactly this value is more important than the design load, as this is the energy that is consumed on average for whole building operation time. It must be noted that this value can only be estimated through complex energy simulation that accounts for hourly changes of external and internal parameters. Also, it is possible that one building can have lower design heating load but higher annual energy consumption. This can happen, for example, in case when two otherwise identical buildings have different windows. If the first building has windows with slightly lower U-value but higher g-value than the second building, then, in theory, it will have higher design heat load, but lower overall annual energy consumption, because the first calculation does not account for solar heat gains.

Similarly, it can happen in case when two buildings have different heating system type. For example, if a building has underfloor heating system, then it can ensure comfortable thermal sensation for occupants with lower indoor air temperature, compared to building with radiator heating. Such results have been showed in studies [2] which analysed three different heating systems (floor heating, hot air blowing heating and radiator heating) using the same heating power. "The results were used to predict the overall thermal comfort in the dwelling model for all the three heating cases. They have shown that for the same heat power in the dwelling, the average indoors temperature is 19.7 °C for radiator heating, 20.4 °C for the low temperature floor heating and 20 °C for the electric heat pump heating. They also showed that the underfloor heating generates a better thermal comfort compared to the two other types of heating. In terms of power consumption, the underfloor heating (due to its high thermal inertia) allows for keeping the system "ON" or "OFF" for longer periods compared to the two other heating systems." Also, if some premises have very high ceilings than by having heating with infrared panels allow to reduce the total amount of provided heating energy, as they directly heat up the surface.

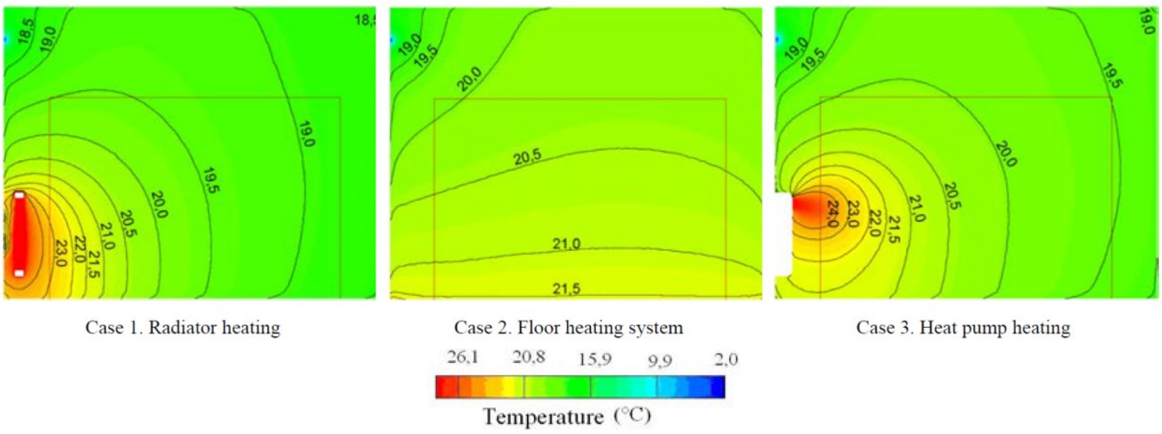

Figure 4.2. *Simulation of thermal comfort on the symmetry plane Z = 0 [2]*

At the design stage when the heating source must be chosen it is done based on the available resources – are there any district heating networks or gas networks, if no, then alternative sources must be chosen. If the customer wants to have sustainable building than in most cases such renewable sources as air-water or ground-water heat pumps air installed.

Existing researches [3] suggest that the air source eat pumps can be a viable solution in case of cold climates: “Due to high efficiency, energy saving, environmental friendliness and safety, the air source heat pump has drawn much attention in the cold and serve cold climate areas. When the ambient temperature is relative high, the air source heat pump’s performance characteristic is relative higher. However, when the air source heat pump is applied to heating in the cold and severe cold area, the refrigerant inspiration specific volume increases along with outdoor ambient temperature reducing, which further causes the decreasing of the heating ability. … In the northern region of China, a two-stage heat pump system composed of air source heat pump unit and water source heat pump (water-air heat pump or water-water heat pump) was proposed which is one of the ideal heating systems, but still in the theoretical and experimental research stage.” However, when installing air heat pumps as main heating source it must always be noted that their efficiency decreases with fall of outside temperature and that during very cold periods mostly electrical energy is used. The decrease of COP relative to outside air temperature is showed in Figure 4.3. Of course, for each specific manufacturer the exact values will differ, but the trend will remain.

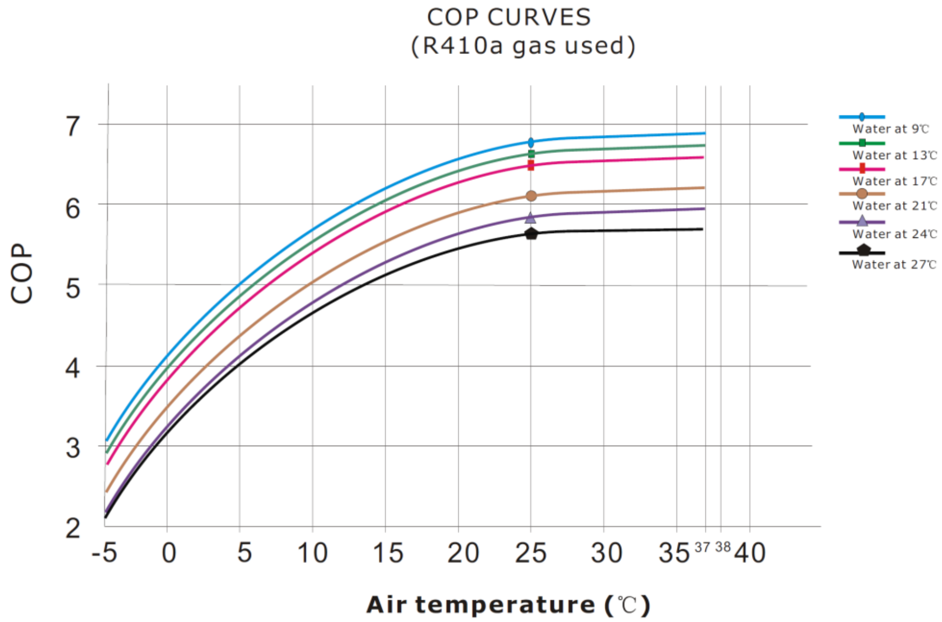

Figure 4.3. *Example of COP variation depending on outside temperature* (http://www.heatpumps4pools.com/koi-ponds2)

As a promising technology to be applied is air cycle heat pump water heaters according to some studies [4] where the performance of ACHPWH was numerically compared with two typical vapor compression heat pump water heaters (VCHPWH) under two different heating schemes, namely instantaneous heating and recirculation heating: “In summary, air cycle heat pump water heater (ACHPWH) is promising to be applied as water heater, especially for instantaneous heating in cold climate. As a last mention, the economy of ACHPWH has not been studied and compared in this work because

ACHPWH is presently more costly owing to the expensive centrifugal compressor and expander.”

Another approach mentioned in studies is to use different refrigerant mixtures to increase the COP and to make the operation of heat pumps more environmentally friendly through limiting use of ozone detoriating gases. For example, a paper [5] presents the results of comparing the energy efficiency of a typical hybrid cold climate heating system, which combined an air-source heat pump and an electric heater back-up with two various refrigerant mixtures. "…Such a system was numerically simulated in order to assess the performance of R32-CO_2 refrigerant mixtures, both for a constant composition of 80/20 and for a variable composition. The refrigerant R410A was used as a reference refrigerant. The seasonal performance analysis demonstrated that by applying R32-CO_2 (80/20), it was possible to save up to 12% in terms of energy consumption. Furthermore, by applying R32-CO_2 with variable mixture, up to 23% of seasonal energy consumption could be saved. Applying R32-CO_2 refrigerant mixture in a heat pump not only will reduce the energy consumption but also will reduce the GWP by 16%, compared to R410A. The obtained results illustrate the benefits of applying refrigerant mixtures in air-source heat pumps with minimum changing requirements in conventional machines.“

Added benefit of using heat pumps as the main heating energy source is their low CO_2 production during the operation time. As the Figure 4.4 shows exactly heat pumps are the heating source that produces the least amount CO_2 in comparison to other most common individual, local heat sources like gas boilers.

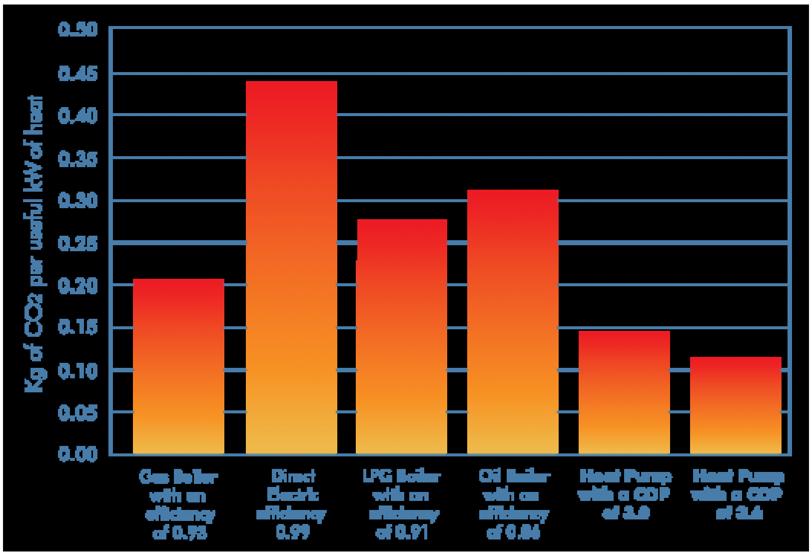

Figure 4.4. *CO_2 emissions for various heating systems*
(http://www.northstarenergy.co.uk/heat_pumps/air_source_heat_ump/)

However, at least in Latvia many buildings are forced to be connected to centralized heating system networks if they are present. But such systems efficiency is also relatively high as in major cities the heating plants work in cogeneration regime simultaneously generating also electricity. The CO_2 emissions from heating plants that use natural gas is established to be 0,202 kg/kWh.

The next step after determining the heat source is to develop a general scheme of the buildings heating system. As this will be the central part of the whole system the solution specifics can both help save the energy and ensure highly comfortable indoor temperature. An example of how such schematic design looks is shown in Figure 4.5. Depending on the building specifics and other HVAC systems, as well as architectural solutions the number and type of separate heating loops or sections must be determined. In most cases there are separate secondary heating loops for underfloor heating, radiator heating and AHU calorifier supply systems. These loops are made separate because each of them has different necessary heat carrier parameters and working regime. The main decision factors and equipment elements that allow to reduce the energy consumption during operation time are the chosen controllers. The higher the automation possibilities the higher the potential to save some energy. Also carefully chosen supply and return temperatures of heat carriers for each loop are important to increase efficiency ratio of used boilers.

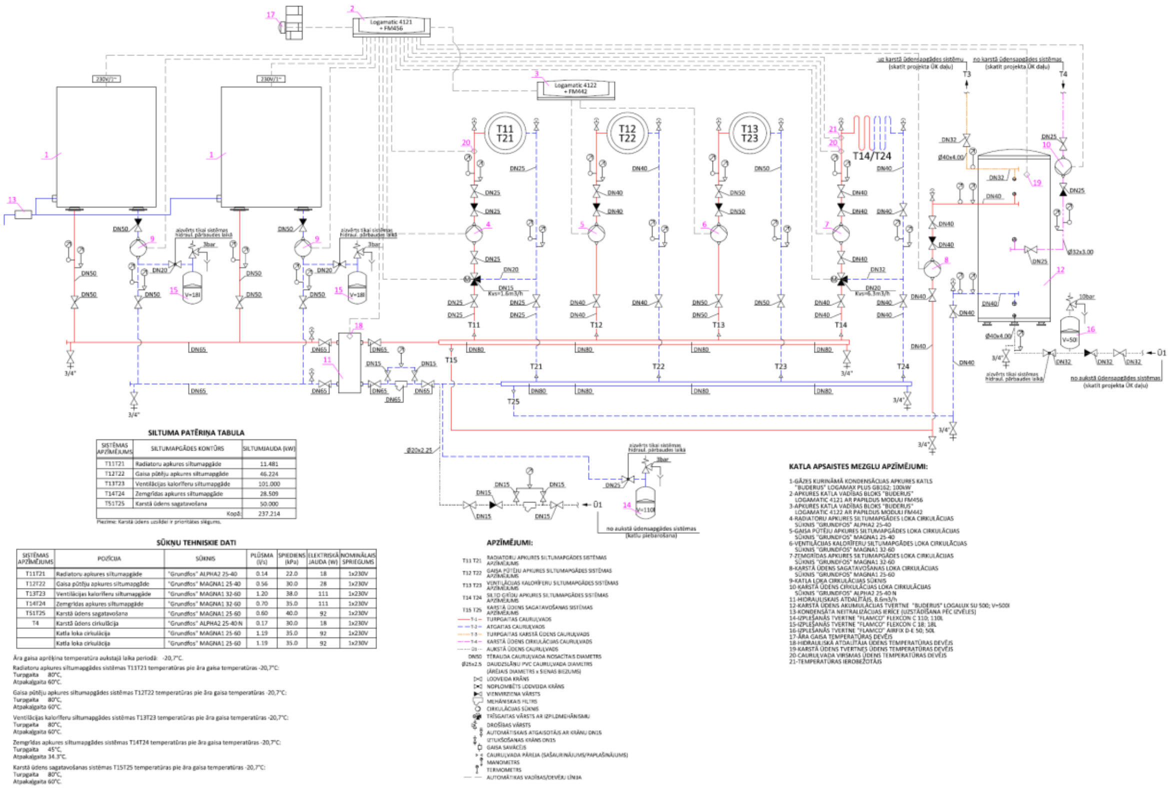

Figure 4.5: *Example of heating systems schematic design*

When the main heating system solutions and elements, like heating source, heating type and pipe layout has been chosen and most of the system calculated and designed it is important to foresee the correct type of balancing. If the balancing valves and their set point are not calculated or chosen improperly it can lead to increased heat consumption due to the fact that the closest heating elements to the heating source will emit more heat than necessary, while the further ones will be to cold. Therefore, the occupants in the closer rooms will have the urge to decrease indoor temperature through opening windows in such way letting out the heat generated in the heating plant. To ensure such situation does not occur the balancing valves are a necessity for heating systems. In the Figure 4.6 three most common types of balancing valves have been showed.

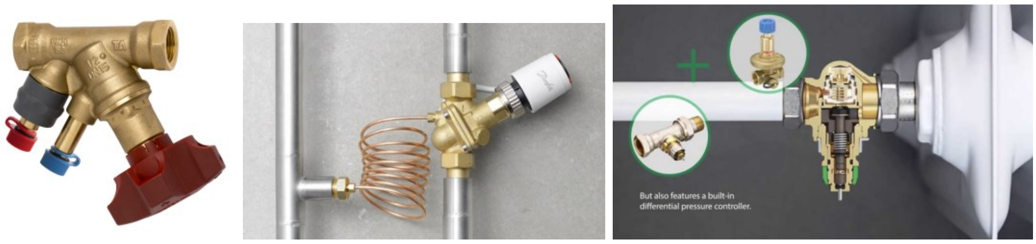

Figure 4.6 *Balancing valve types: manual (on the left); combined automatic balancing valve (middle); dynamic (on the right)*
(http://www2.imi-hydronic.com and http://products.danfoss.com)

The importance and benefits of heating system balancing have been widely studied and the consensus is that by applying balancing function the overall energy consumption reductions is around 5-15%. Depending on where the valves are located and how they operate the balancing valves can be divided in three subgroups: manual valves, combined automatic balancing valves or dynamic valves. The most common ones which very mostly used for heating system balancing some time ago are the manual valves. They have pre-set values and for each value and valve size combination the flow and pressure loss through the valve is given. By knowing this it can be determined at which position the valve must be set to achieve the necessary system parameters for design conditions. However, as the heating system parameters vary during the year this valve is not capable to adapt. Therefore, combined automatic balancing valves can be used. They integrate three functions in one valve - a differential pressure controller, a flow limiter and a zone controller. For them to work they valve must be coupled with partner valve that is located on return pipe of the same system. The AB-PM valve converts an unbalanced variable flow system into a reliable and balanced heating system with proper heat distribution, even at partial loads. Thanks to the stable low differential pressure across all the thermostatic radiator valves, the heating system also becomes noise free. At the same time the most advanced solution would be to use dynamic balancing valves as they combine also the thermostatic radiator valves with the differential pressure controller for accurate temperature control and automatic hydronic balancing in a single product. As these valves are located on each radiator the system will remain in perfect balance regardless of any temperature or flow fluctuations because the valve will keep the pre-set flow regardless of pressure changes in the heating system, making each radiator independent.

4.4. Ventilation system

The second most important mechanical system in nZEB is the ventilation system. In nZEB cases it is especially important as the building is maximally air tight and the energy loses through building envelope are reduced to minimum. In such cases the heat needed for ventilation air heating can easily reach up to 40% and more depending on the building type. Because it is possible to reduce the heat loses through building envelope but the ventilation is necessary in any case and as we cannot regain 100% of exhaust air energy there will be some heat loses due to ventilation. And the will be relatively higher as the building gets more insulated. Therefore, it is vitally important to design the ventilation system in such way that regenerates as much heat as possible and can be precisely controlled.

As the local regulations require that at least 75% of heat from ventilation system is recovered it means that there should be some kind of mechanical ventilation system in the building. In general, there could be two solutions – either fully mechanical ventilation system with air handling unit or, in case for apartment buildings, decentralized ventilation system with room based heat recovery systems

The ventilation system design can be divided in several subtasks:

1) Calculating the necessary ventilation air volume
2) Estimating the annual energy consumption for heating
3) Choosing and designing the ventilation system type
4) Designing and calculating rest of the system elements, like, air ducts, flow dampers, diffusers, insulation, silencers, fire safety valves, etc.

4.5. System installation stage

After the designing stage of all the systems and building the building and installation of engineering networks can be started. During this stage a lot of potential mistakes can be made if the involved personnel is not up to task or lack some specific knowledge for installation works. This can lead to severe malfunctions of designed engineering systems and increased energy consumption that can afterwards be difficult to explain due to fact that a lot of the problems could be hard to spot because the engineering networks most often are installed either in walls, ceilings or under the floor. The importance of the installation mistakes can vary from simple aesthetics problems or annoyance, if something is not installed to be good looking or according to ergonomic requirements, up to serious danger causing, life or health threatening mistakes. However, the most common ones are some small installation mistakes or inaccuracies that cause increased energy consumption, noise generation, lifespan shortening of devices or system elements, decreased automation capabilities and general minor system working problems.

The first and least important or influential group of installation mistakes are the ones that cause some aesthetic displeasure or make the system elements hard to access. This, although, in short term do not directly cause damaging effect in longer time period can cause some problems, because the inaccessible elements will not be maintained as needed and therefore can cause some problems in future. Such situation can often be seen for various kinds of elements that need regular maintenance but lack access hatch or are installed in a way that other elements block them. Some of the most common cases with such situation are ducted air cooling devices with lack of access cover, revisions for sewerage or cleaning places for ventilation air ducts that are hard to reach, filters for various systems, balancing valves behind other systems or similar cases. In the Figure 4.7 an example of such an installation example has been shown. It shows an air intake grill that has been located behind decorative wooden façade elements and during the operation period it has clogged up with dust that comes from nearby construction process as this building is located in a new open place area where other buildings are only now being built. Quite often similar problems can be avoided during design stage, by foreseeing all the necessary access elements and ensuring enough space so the system elements can be easily accessed and maintained. The problem occurs when, due to visual reasons, the number and size of access covers is minimized, and all of the engineering equipment elements are hidden as much as possible.

Figure 4.7: *Hidden ventilation air intake grill clogging with dust*

The second group of installation mistakes are the ones that can cause increased energy consumption of the designed systems and shortening of equipment serving lifetime. An example of a typical such mistake can be seen in Figure 4.8 which shows a circulation pump that is installed in wrong position. This can cause higher electricity consumption during system operation as the pump works with lower efficiency, but more importantly it can cause the breakdown of the pump due to overheating as the liquid is not passing through it as foreseen by manufacturer. Such incorrect pump installation can be seen quite often despite the fact that the manufacturer includes an installation manual with each pump package and the brand name is always especially oriented in a way that it can be read.

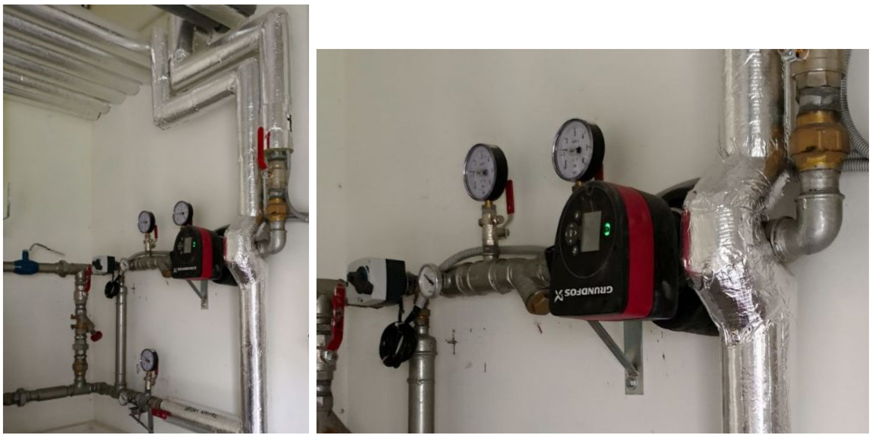

Figure 4.8: *Incorrect installation of a circulation pump*

Another example in this installation mistake group could be mentioned deviations from design solution regarding air duct material or size or not respecting the manufacturer requirements for straight pipe/duct lengths before various elements. The figure Figure 4.9 shows how in a project the ventilation air duct material is changed to flexible type compared to hard tin sheet air duct. This can cause increased pressure drop in the system therefore causing higher electricity consumption in AHU and higher noise generations. Such relatively small deviations from project solutions are often done by builders to save time and money but can cause issued during system operation time. Sometimes, if the building supervisor does not have specific knowledge this can go unnoticed. Similar small inaccuracy’s related to the required straight pipe or duct sections before various elements like valves, flow meters, silencers are also often neglected both due to space limitation but more often due to shortage of time and not wanting to pay attention to smaller details. This can cause increased noise levels, inaccuracy of readings of flow meters and overall performance degradation of system as the valves will not operate as calculated.

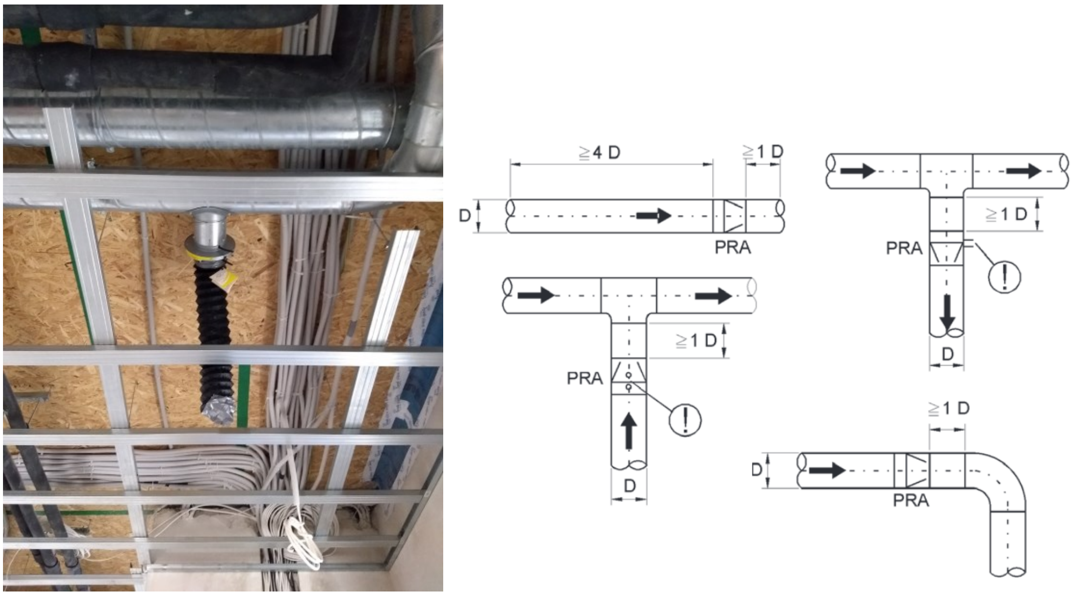

Figure 4.9: *Installation of flexible instead of tin air duct (left side), manufacturer recommended safety distance for valve installation (right side)*

The third group of installation mistakes can cause technical problems during exploitation of building and can be visibly detected. For example an inappropriate pipe material selection or connection of two different pipe materials that should not be connected can be mentioned. One such example is connection of copper and galvanized steel pipes. They should not be joined directly because it will cause galvanic corrosion therefore forming of a leak, see Figure 4.10. To avoid this at each connection a separation of these two metals must be made with a brass fitting, or a specific dielectric union. Also, some plastic pipe material must be specifically used for hot or cold water, like PVC-U is made for cold water while PVC-C for hot water. In this group of installation mistakes such mistakes as inappropriate air duct cutting by using angle grinder instead of specialized air duct cutting equipment can be mentioned. By using angle grinder, the small protective layer of tin sheet air ducts is damaged, and the air leakage increased. Similar problems can occur when mounting hydronic systems, if for example pipes are from one manufacturer but pipe fittings from another. This, due to small size and type differences, can cause pipe joint places and bends to be not as strong as needed and they will have higher potential of leakage. This is another relatively often occurring problem because the good quality pipe fittings are noticeably more expensive compared to other ones.

Figure 4.10: *Corrosion of piping at joints and bends*

The last, and potentially, most importantly, the installation mistakes can be related to low voltage and BMS elements that operate and regulate all the HVAC system. This is the most important part of the whole system because it is responsible for all the other built system elements. If it will be dysfunctional it can cause noticeable increase in energy consumption or decrease in comfort level. Also, it is harder to notice that something is not working as designed in low voltage or BMS systems in comparison to other HVAC system elements because usually there are no visual indicators. In most cases standard persons maybe has the general knowledge regarding the mechanical systems and can identify a problem if something is visually leaking, emitting high noise, moving suspiciously, or not heating/cooling/venting noticeably but if the problem is related to low voltage than rarely a person can identify it. For larger and more advanced buildings the BMS can be very complex with high amount of variable parameters that controls the mechanical parts and only highly qualified specialist can truly understand all the working algorithms. Only in some simpler cases like presented in Figure 4.11 the local system HVAC system manager can identify the problem.

Figure 4.11: *Example of incorrect installation of valve regulator*

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Conclusions

Design, installation, operation and human behaviour factors impact on the energy consumption of heating, cooling and ventilation systems for nZEB. The best solutions are always the ones that are self-sustainable, failsafe, easy to understand and control and have high level of reliability.

The first step in successful completion of nZEB is to have high quality and integrated design. Designed systems must serve the specific building acknowledging the location, architectural design, premise usage type, available energy resources, etc. We recommend to perform analysis and energy calculations of various scenarios to find the one most suitable for given building, using such energy simulations as IDA-ICE, IESVE, Energy+, RIUSKA software. The main decision factors and equipment elements that allow to reduce the energy consumption during operation time are the chosen controllers.

When the main heating system solutions and elements, like heating source, heating type and pipe layout has been chosen and most of the system calculated and designed it is important to foresee the correct type of balancing. The importance and benefits of heating system balancing influence energy consumption reductions is around 5-15%. Balancing valves can be divided in three subgroups: manual valves, combined automatic balancing valves or dynamic valves. The most advanced solution would be to use dynamic balancing valves as they combine also the thermostatic radiator valves with the differential pressure controller for accurate temperature control and automatic hydronic balancing in a single product.

After the design stage of all the systems and building, the building and installation of engineering networks can be started. It is important to show major influential group of installation mistakes:

- the ones that cause some aesthetic displeasure or make the system elements hard to access, as inaccessible elements will not be maintained as needed and therefore can cause some problems in future.
- the ones that can cause increased energy consumption of the designed systems and shortening of equipment serving lifetime. Deviations from design solution regarding air duct material or size or not respecting the manufacturer requirements for straight pipe/duct lengths before various elements.
- mistakes can cause technical problems during exploitation of building and can be visibly detected.

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References

[1] Borodinecs A., Rodriguez-Gabriel A., Tatarchenko O., and etc. Handbook on Buildings Renovation in Central Baltic Region – ISBN - 978-9934-507-39-7 – Riga: Riga Technical University

[2] F. B. Errebai, L. Derradji, M. Amara, Thermal Behaviour of a Dwelling Heated by Different Heating Systems, In Energy Procedia, Volume 107, 2017, Pages 144-149, ISSN 1876-6102.

[3] Zhijian Liu, Yifei Wang, Zhiping Xie, Hancheng Yu, Wensheng Ma, The related problems and development situation of air source heat pump in the cold and serve cold climate areas, In Procedia Engineering, Volume 205, 2017, Pages 368-372, ISSN 1877-7058.

[4] Liang Yang, Han Yuan, Jing-Wei Peng, Chun-Lu Zhang, Performance modeling of air cycle heat pump water heater in cold climate, In Renewable Energy, Volume 87, Part 3, 2016, Pages 1067-1075, ISSN 0960-1481

[5] Ali Hakkaki-Fard, Zine Aidoun, Mohamed Ouzzane, Improving cold climate air-source heat pump performance with refrigerant mixtures, In Applied Thermal Engineering, Volume 78, 2015, Pages 695-703, ISSN 1359-4311.

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