Influence of recirculation strategies in collective heat distribution system on the performance of dwelling heating substations

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The aim of this study is to assess the influence of different recirculation control strategies in collective heat distribution system on the performance of dwelling heating substations and network heat losses, so that decision maker can potentially identify the optimal operational conditions of this system component. To that aim, six different heating substation models are set up (using TRNsys) for investigation of the energy-efficiency and comfort issues. Regarding control strategy the effects of different recirculation methods: continuous and constant, centralized and temperature controlled and customer unit controlled are examined. Different types of substations such as storage tanks either equipped or not equipped for in-situ hot water preparation, interaction between space heating and domestic hot water circuits as well as, direct or indirect connection of dwelling space heating system are also investigated. Temperature drops in supply pipes of the distribution network during summer months due to low heat demands of consumers and heat losses at each scenario are compared. The first results indicate that the design concept of the substation in relation with the actual operational conditions has an important impact on the energy performance of the entire system.

Keywords: Water recirculation in heat system, District heating substation, Network heat losses

INTRODUCTION

Collective heat distribution systems at the level of building or communities (district heating) is seeing more and more as an effective solution towards sustainability in the heating sector. In this context, during the last years it has been demonstrated that low-temperature district heating (supply temperatures lower than *65°C*) is the next evolution in district heating systems [1]. Low-temperature district heating system aims to reduce heat losses from network as much as possible, meanwhile maintain or improve level of comfort for users. Reduction heat losses in the distribution network clearly contributes to the energy-efficiency of the entire system. While, domestic hot water comfort is considered in function of temperature of tap water delivered and the time required for domestic hot water (DHW) to reach a fixed temperature level after tapping was started, the so called waiting time. In addition to the level of DHW comfort in terms of temperature and waiting time, attention should be paid to the general guides for legionellae control in DHW-systems. The hygienic requirement for heating of DHW due to recent standards is *50°C* for single-family houses and *55°C* for multi-family buildings [2].
Together with comfort surveys, these requirements are based on the need to avoid legionella growth in DHW pipes and storage tanks. It should be mentioned that requirements to produce DHW with temperature higher than *50°C* is especially more important for collective heat distribution system (CHDS) with old design approaches containing vertical riser, branched pipes with bigger diameter (increasing water volume of the distribution circuit), or centralized bigger storage tank. In new and/or renovated buildings, heat system are designed with reduced pipe diameter, defined by requirements for noise propagation and pressure drop, separates connection of DHW pipes between each tap and source of DHW and in general the length of the DHW-pipes in the dwellings is shorter than *5m* and the volume is lower than *3L*, in order to avoid that water at unsafe temperatures remain still for a long time in the distribution circuit [3;14]. Although, growth of legionella in DHW system is not in focus of this paper, the risk of increases legionella growth in the range of temperature between *20°C* and *42°C* was taken into account. For readers interested in this topic, more comprehensive discussion regarding DHW systems and legionella issues can be found in [4;5;6]

It is well-known that in CHDS supply temperature drops during the summer months due to low heat demands of consumers. Hence to avoid service pipes to cool off in summer time in collective heat distribution system when there is no heat demand for space heating, by-pass valves are installed in the system between the supply and return pipes. The resulting by-pass flow decreases the temperature difference, but this is necessary in order for the substation to be able to deliver domestic hot water at the requested temperature. This operational strategy carried out to warrantee the availability of hot water in the system at any time is defined as recirculation.
The aims of this study is to assess the influence of different recirculation control strategies in collective heat distribution system on the performance of dwelling heating substations and network heat losses. To that aim, six different heating substation models are set up (using TRNsys) for investigation of the energy-efficiency and comfort issues. Several recirculation methods: continuous and constant controlled, centralized and temperature controlled and customer unit controlled are examined. Different substation types such as storage tanks either equipped or not equipped for in-situ hot water preparation, interaction between space heating and domestic hot water circuits as well as, direct or indirect connection of dwelling space heating system are also investigated.

RESEARCH FRAMEWORK AND STUDY BOUNDARY CONDITIONS

Literature review and state of the art

Nowadays research surveys regarding collective heat distribution system, low temperature district heating systems and simulation assisting energy systems improvement are commonly found in the scientific literature. Recently a numerical modeling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of domestic hot water was presented by Brand (2012) [3]**.** By using a substation model that takes into consideration the effect of service pipes the authors demonstrated that the way in which the service pipe is operated has a significant effect on waiting time for DHW, heat loss, and overall cost. In the same way, the performance of two consumer units for a low temperature district heating net was investigated using TRNsys in [7]. While Rämä and Sipilä (2010) studied the problem on low heat density district heating network design in a representative case of a low heat density area [1] .
A comparative study on substation types and network layouts in connection with low-energy district heating systems was reported by Hakan (2012). The network layout, additional booster pumps, and different substation types such as storage tanks either equipped or not equipped in domestic hot water production site were also examined [8]. Paulsen (2008) studied substations equipped with differential pressure control valves that adjusted the flow on the primary side (where the DH medium is circulated), in accordance with the heat demand requirements in order to achieves a hydraulically balanced distribution throughout the DH network [9]. An experimental evaluation of radiator control based on primary supply temperature for district heating substations was presented by Gustafsson (2011) in [10]. The author, demonstrates that it is possible to control the radiator system based on the primary side supply temperature, however, conclusions regarding improvements in differential temperature were hard to distinguish [10].

Case-study collective heating systems

The model of building, the collective heat distribution system and the development of the integrated dynamic simulation model was built in accordance with the methodology explained in [11;12;13]. The case-study collective heating systems are designed for a multi-family building with 25 dwellings on 5 floors. The CHDS distributes heat for space heating and domestic hot water preparation from a central plant in the basement to the individual apartments, which are equipped with the customer substation. The analysis was carried out for a low-energy building with a heat supply temperature of *60°C* to the substations and highly insulated collective heat distribution pipes. The space heating system is based on radiator with supply temperature of *60°C* and return temperature of *40°C* with variable supply temperature in function of the outdoor ambient temperature as control strategy.
The apartments heat demand for space heating and domestic hot water are calculated with the Flemish building energy performance (EPBD) software. Three types of apartments were designed, with different floor areas (*90* to *150*m^2), and different thermal performance. The resulting net energy demand for space heating of the apartments is between *15* and *30*$kWh/m^2/year$, so the dwellings are low-energy or passive dwellings [11]. The domestic hot water demand only dependent on the dimensions of the dwellings. Table 1 summarizes the information regarding the selected dwellings.

Table 1: Energy use of the three type of apartments in the building

Type of House in the building	Number of house	Area (m^2)	Volume. (m^3)	Space heating ($kWh/m^2/year$)	Hot tap water (kWh/day)
1	10	90	312	15	2.7
2	5	119	427	22	3.5
3	10	148	490	27	3.9

Base case simplified calculation methods

As was observed by Himpe (2014), in calculations of the energy performance of buildings in Europe according to the EPBD, the heat losses in collective heat distribution systems are usually incorporated [12]. If the energy performance is calculated per month, the calculation of heat losses in the distribution network is based on the general formula:

$$Q_{loss,net,m} = t_{net,m} \times \sum_j (\theta_{net,m} - \theta_{amb,j,m}) \times \left(\frac{l_j}{R_{l,j}}\right) \; [MJ] \tag{1}$$

In which $t_{net,m}$ is the monthly operation time of the distribution network, $\theta_{net,m}$ is the monthly average temperature of the heat conducting medium in the network, l_j is the length of a pipe element *j*, $R_{l,j}$ is the linear thermal resistance of this pipe element and $\theta_{amb,j,m}$ is the average temperature of the pipe environment. The parameters in the general equation (1) are defined according to the local legislative EPBD-implementations and standards and to the type of system. Dependent on the final use of the heat, three types of CHDS are recognised: systems that serve heat for space heating only, for domestic hot water only and for combined space heating and domestic hot water production. In this last type of systems, the collective heat is used to generate domestic hot water in the local substations [12].

The dynamic simulation results are compared to an existing simplified heat loss calculation method (*EPB_Combilus)*, that is the Flemish/Belgian simplified calculation method for distribution heat losses in systems for combined space heating and domestic hot water production. The method starts from equation (1) and defines the monthly working time t_m of the system as the length of an entire month, and the average temperature of the heat conducting medium in the network is the maximum of *60°C* and the monthly average temperatures in the space heating emission systems. In this case-study, the monthly average temperature in the space heating systems is *50°C*, so $\theta_{net,m}$ is *60°C* [12].

Recirculation control strategy scenarios

As was aforementioned three scenarios of recirculation control strategies have been examined. The first scenario considers continuous recirculation control strategy (CR) in the collective heat distribution system. Traditionally, recirculation system are controlled by a thermostat, however in this case the temperature is not take into account, thus the recirculation is operating continuously during the period of not demand. In other words, the set point temperature of the bypass element is set up to keep the temperature at the level of DHW supply, that means T_{set_bypass} equal to *60°C*. The second case is based in a more widely used recirculation control system based on centralized and temperature controlled recirculation strategy (CTR). In this option the thermostat is controlled using an adjusted set temperature to ensures that the temperature in the supply pipes kept within the operational range of *35°C* and *50°C*. The practical solution of this option consists of a pulse controlled bypass with a set point temperature T_{set_bypass} and a "dead-band", which defines a top and bottom bypass set point temperature. The dead-band of the self-acting controller of the bypass behaves as an on/off switch causing the pulse effect. A pulse bypass cycle consists of a period of water flow from the main distribution line to the service pipe (called the "bypass" period), and a period when there is no flow and the water inside the supply service pipe cools down (the "stand-by" period) [14]. The bypass valve operating with this controls strategy are usually installed at the top of the riser supply service pipe at each stair for the case of multi-family building and/or in each street pipe for the case of detached dwelling [15].

The third scenario considers local customer unit controlled (LTR) as recirculation strategy of the CHDS. In this alternative a bypass valve installed in each house substation is considered. In our investigation we study the case of internal bypass which maintain a small flow of primary side hot water through the DHW heat exchanger. In contrast to the previous case here the bypass flow don't stops instantaneously when the temperature of bypass water at the outlet of the service pipe reaches a specific value. Hence a small flow kept continuously at bypass standby temperature going through the DHW heat exchanger. A self-sensing temperature regulator indexed in the plate heat exchanger controls the hot water temperature and activate a small and variable flow rate (around *0.003 L/s*) when the temperature drop below *50°C* degrees during long period without DHW demand [16]. In the case of substations with storage tank this specific control is not installed, however in this study the charging period of the storage tank is considered as a local customer controls of the recirculation in the CHDS.

Study cases of dwelling heating substations

A substation is a component which connects and separates the collective part of a distribution heating system and the parts within the individual dwelling. In general there is no an internationalization standard of dwelling heating substation configurations. However as a result of the actual tend of energy demand in building reduction and new collective distribution heating systems design concepts considering supply temperature to be reduced as well, nowadays, more and more compact and prefabricated substation unit are preferred. Substations can be classified according to several criteria based upon the operation mode of existing applications. Thus, substations can be classified according to *a)* secondary space heating circuit connection, *b)* type of recirculation control, *c)* interaction of space heating and domestic hot water circuits, *d)* type of domestic hot water preparation and *e)* type of configuration. Below, table 2 summarizes the different classification criteria.

Table 2: Summary of classification criteria and configuration dwelling heating substation.

<table>
<tr><td rowspan="5">Classification criteria</td><td>SH Connection</td><td>Direct</td><td>Indirect</td></tr>
<tr><td>Recirculation Control</td><td colspan="2">Continuous   Central control   Local control</td></tr>
<tr><td>Interaction SH and DHW</td><td colspan="2">Independent   SH and DHW Interaction</td></tr>
<tr><td>DHW preparation</td><td>Instantaneous heater</td><td>With storage tank</td></tr>
<tr><td>Configuration</td><td>• Serial
• Indirect Parallel
• 2-Stage
• Double 2-Stage
• 3-Tage
• Direct Parallel</td><td>• Buffer tank with annular SH
• Coil inside and annular SH
• Coil inside tank
• External heater of buffer
• With thermal desinfection
• External DHW heat exchanger
• External DHW heat exchanger and SH bypass</td></tr>
</table>

In our analysis priority have been provided to single houses substation since one of the mains focus of this study is the comparison of different alternatives with a substation configuration that is used in a real life case-study: a low-temperature residential CHDS in the city of Kortrijk in Belgium [17]. In this study six types of substations for space heating and domestic hot water are regarded (see figure 1).

Figure 1 *a)* shows a substation with instantaneous preparation of DHW by mean of a heat exchanger and direct space heating connection (IHE_DSH). These two features are also included in case *b)*, but a bypass from the space heating return pipe to the space heating supply pipe allow the implementation of variable supply temperature as a control strategy of the space heating circuit (IHE_DSHbyP). Figure *1 c)* displays a customer unit with instantaneous preparation of DHW and indirect space heating connection (IHE_ISH). The indirect substation type have two heat exchangers for transferring heat from the primary water flow of the network to both the tap water and the dwelling SH system. In contrast to the previous configurations, substations in figure 1 *d), e)* and *f)* are customer unit with storage tank in the DHW circuit. However, there are significant differences between these three configurations. Figure *1 d)* presents a substation with domestic hot water stored in the tank as well as, there is a coil inside of the buffer tank, (DHWST_Coil).

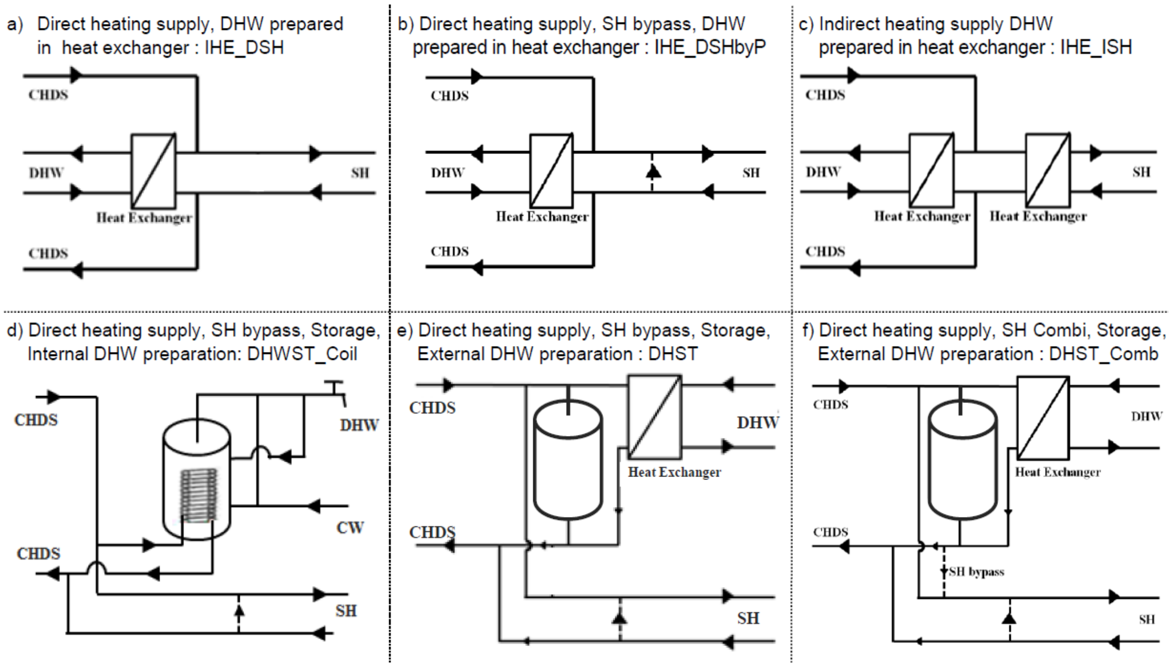

Figure 1. Configuration of dwelling heating substation investigated.

The substation with domestic hot water in the storage tank is not able to fulfill the up-to-date design recommendations as prescribe for instance in the Best Available Practices for public collective systems in Belgium [18] or the German standard DVGW 551 [19]. As was pointed in the introduction, new design concept recommends that the water volume in the dwelling DHW system cannot be more than *3L*. This requirement will be not met by this traditional substation configuration with DHW inside of the storage tank, usually accounting for *100-175L* for a single family house. For that reason new generation of substations with storage tank tend to use an external plate heat exchanger instead of inside coil for domestic hot water preparation. The storage tank position have been moved to the primary side circuit and stores primary side hot water instead [20]. This characteristic is presented in both configuration shows in figure 1 *e)* and *f)* where DHW is prepared on the instantaneous principle in the heat exchanger by using water coming from the storage tank. In the case of figure 1 *e)* (substation: DHST) there is no interaction between the DHW and space heating circuits. While figure 1 *f)* displays a configuration whit interaction between DHW and SH circuit by means of a bypass at the bottom of the storage tank (DHST_Comb). A more detailed description of this type of substation can be found in [13; 20]

RESULTS ANALYSIS

Return temperatures from the substation to the network

In the distribution system the temperature produced at the plant is *62°C* and the design temperature at the substation is *60°C*. The return temperatures from the substations of the three different dwelling types were analysed in detail, based on simulation results with a time-step of 5 s. during winter and summer conditions. In figure 2 the return temperature from the substations are summarised per recirculation control strategy for one week simulation during summer season. The results from the 3 different dwelling types were integrated, taking into account the proportions in which they appear in the multi-family building.

As have been already mentioned, the three variants of recirculation control differ with regard to the control variable and the location of the bypass valve in the heat distribution system. When continuous recirculation control strategy is used, results denote that the six analysed substations present high value of return temperature. Although, in each substation some values of the sample are around *20°C*, much of the value are above of the *55°C* as denotes the box around the median value of the sample of each substation.

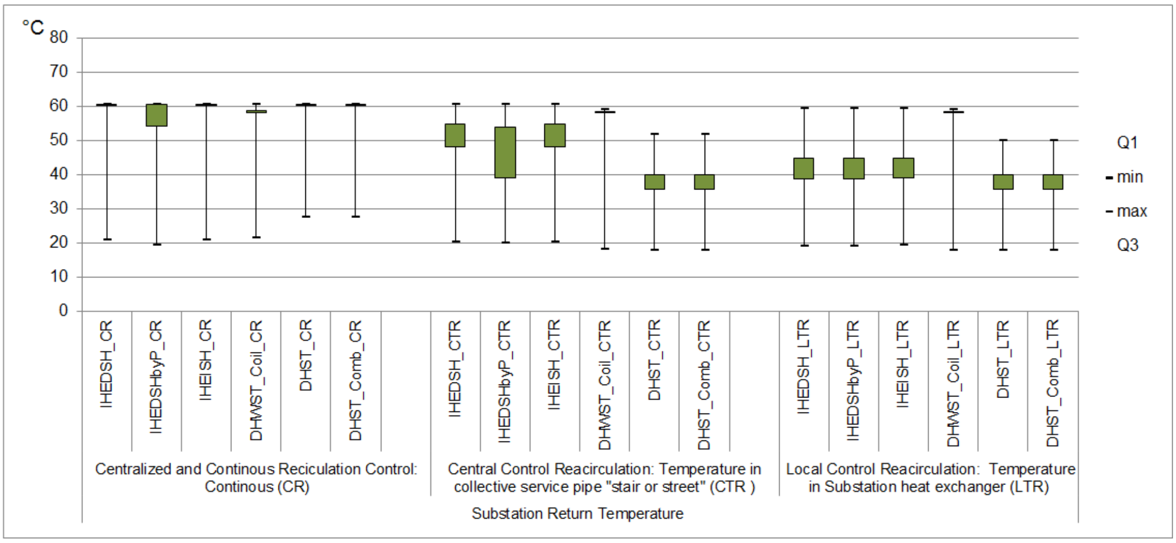

Figure 2. Substations return temperatures per recirculation strategy during a summer week

A different behave appears when temperature is used as decision variable of the control strategy of the recirculation. On the one hand when the recirculation is carried out using a centralized temperature control with bypass valve located at the top of the stair (or at the end of the street), the two substations with storage tank and external heat exchanger for DHW preparation (DHST and DHST_Comb) reach values of average return temperature around *38°C*. In this scenario with centralized temperature control of the recirculation those substation with instantaneous preparation of domestic hot water presents temperature on average around 51°C. The substations with direct space heating supply and with bypass between the return and supply pipes of the SH have an average return temperature of *45°C*. On the other hand when the temperature at the substation heat exchanger is used as a control variable of the recirculation, the average return temperature of substations without storage tank remind on average around *42°C*.

In addition, when comparing results of CTR and LTR scenarios, it is remarkable that there are not too much difference in the performs of the two substations with storage tank and external heat exchanger for DHW preparation. This result can be due to the fact that the charging control strategy of the storage tank overrides the recirculation controls, since both recirculation control strategies (centralized and local) use temperature as a control variable. It should also be noticed that the substation with DHW in the storage tank, DHWST_Coil, always presents average return temperature above *57°C*. This behaves is a result of the charging control strategy that have to warrantee high level of temperature inside of the storage tank all the time due to hygienic requirements since DHW is stored in the tank. In general, when considering the different scenarios and substation configurations, seven cases can be identified which presents better preforms with average return temperatures below *42°C*.

In figure 3 a more detailed analysis of this seven study cases is displayed. The return temperatures of the selected cases at several operational modes are summarized. Five of the seven cases correspond to the scenario of local temperature control strategy of the recirculation, while the other two cases are from the option of centralized temperature control of the recirculation. Beside the evident difference between the analyzed substations with regard to the use or not of a storage tank for DHW preparation, much of the configurations difference are related with SH circuit. Noted that, for instance, the use or not of bypass between supply and return pipes in the SH circuit, as well as, the use or not of heat exchanger separating the primary and secondary circuit of the space heating or even if there is interaction between the discharge outlet at the bottom of the storage tank and the space heating are peculiarities of the different study cases. Since the study is focused in the influence of the recirculation controls strategies, the analysis is carried out for a week during summer season. As a results, the characteristics of the substations regarding space heating circuit have not a significant impact on the total return temperature. This situation explains the correspondence between the results during the stand by period and the whole substation for each study case. The graph also shows that the return temperatures during domestic hot water generation are on average *23°C* and vary between 21 and *31°C* in the substation without storage tank. The domestic hot water average return temperature of the substations with storage tank and either with and without bypass to the SH circuit presents values around *39°C*.

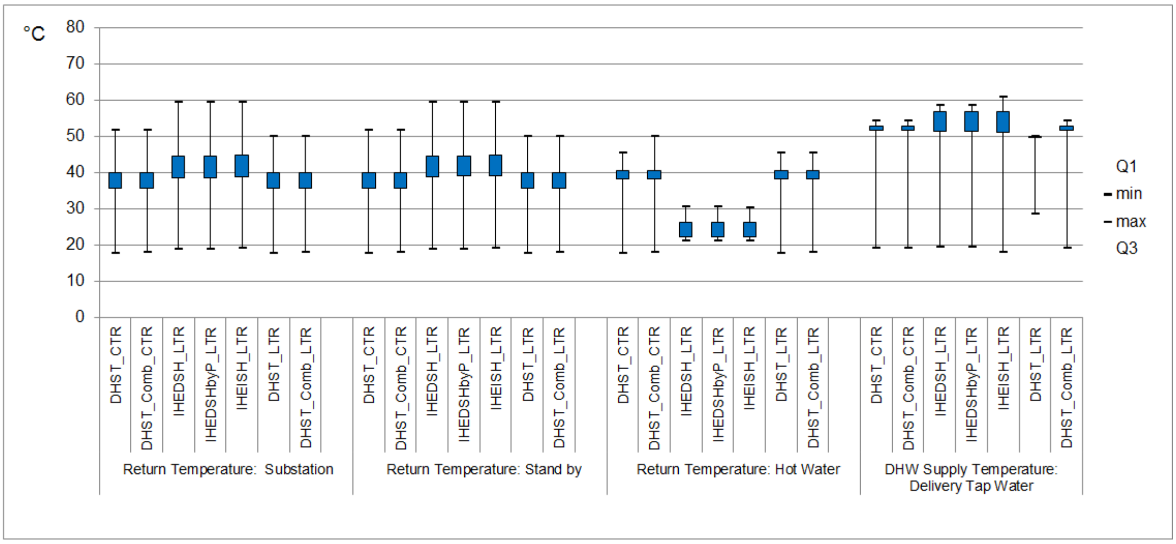

Figure 3. Substations tap water supply and return temperatures at different operational mode

As a result of the storage charging period a small amount of water from the bottom of the tank with temperature between *35°C* and *40°C* remain still in the pipe during idle function and increases the return temperature coming from the DHW heat exchanger during the first seconds of domestic hot water demand. In addition to the return temperatures at different operational modes of the substations, the supply temperature of hot water delivery at the tap has also been displayed. Results denote that all substations are able to warrantee domestic hot water with temperature above of the *50°C*.

Return temperatures at the plant level

Figure 4 displays the monthly average temperatures of the collective heat distribution system at return pipes near the central plant for all studied cases. As expected, for all of the studied cases the return temperature remind above of the *52°C* during the whole year when a continuous recirculation control is used. In terms of return temperature at plant level, the best performance is achieved by substations with storage tank when both centralized temperature and local temperature control strategies for recirculation are used. When local temperature control strategy for recirculation is used, substations without storage tank presents a satisfactorily performance as well. In summer the three substations with instantaneous DHW preparation, (i.e. with and without bypass in the SH circuit and with and without heat exchanger in the SH) performs in a similar way. However, during the heating season, in winter, the substation with direct space heating and bypass (IHEDHSbyP) presents a better performance.

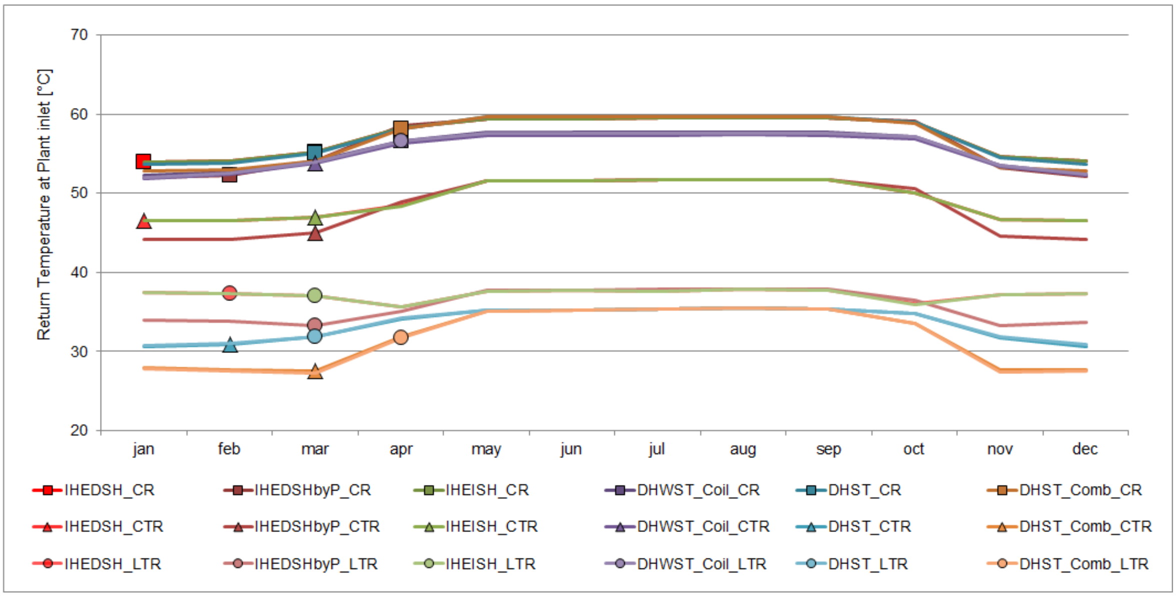

Figure 4. Monthly average temperatures in the return pipe near to the heating plant

In systems with this substation type and LTR control strategy cooling-down of the network leads to monthly average return temperatures at the central plant of around *33°C* in winter and *38°C* in summer. In term of return temperature at plant level substation with storage tank and bypass to the SH presents a better performance than the one with storage tank without interaction between DHW and SH circuit. Similarly, in systems with substation with storage tank and recirculation control strategy based on centralised and/or local temperature, the monthly average return temperatures at the central plant reach value somewhat around *28°C* in winter and *35°C* in summer.

Heat losses in the distribution network

Figure 5 illustrates the distribution heat losses for the different variants analyzed. The heat losses are slightly higher in winter than in summer, as a result of the higher temperature of the heating medium and the lower temperature of the pipe environment. However since the pipes are located in an unheated part but inside of the building, the seasonal temperature variation both inside and around the pipes is not so significant. Therefore, the differences between summer and winter season are smaller than 10%. When continuous recirculation is used, substations with storage tank and external heat exchanger performance worse than substation without storage. When local and centralised temperature control of recirculation is used in substation with storage tank, the heat losses are in the same level that those of substations without storage tank using centralised temperature control of recirculation. Although, the effect of the reduction of pipe diameter in the distribution network and the decrease of flow rate requirements during operation when substations with storage tank are used, the losses in the storage tank and the heat exchanger have a significant impact in the total heat loss of this kind of system. It should be mentioned that substation with DHW in the storage tank presents a good performance independently of the recirculation control strategy. Since, there is no heat exchanger in this kind of substation, the significant amount of additional heat losses corresponding to the heat exchanger is avoided. When local temperature controls of the recirculation is used, the heat losses of substations without storage tank are 10% lower than the heat losses of substations with storage tank.

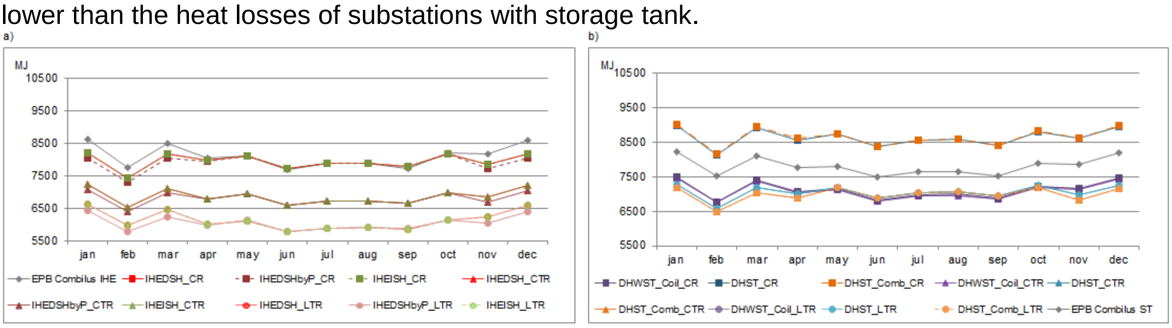

Figure 5. Monthly heat losses in the distribution network for the different variants analyzed

In the above graphics it is possible to identify different categories of performance depending of the use or not of storage tank and type of recirculation control strategy. In the case of substations with instantaneous preparation of DHW three categories can be defined in correspondence with the recirculation control strategy. However, in the case of substations with storage tank only two categories can be defined. Result denotes that for the case of substation with DHW in the storage tank there is no significant impact of the type recirculation control strategy. For the three recirculation scenarios the monthly heat losses reminds around *7000 MJ*. On the other hand those substations with storage tank in the primary side circuit can be grouped in the similar category for both local temperature and central temperature controls strategies of the recirculation.

A further operational criterion to access the performance of the collective heat distribution system is the relative heat loss (in the distribution system). The relative heat loss in the distribution system, *RHL* (in percent) is a characteristic parameter widely used in the field of district heating systems for defining the effectiveness of the DH networks. The relative heat loss is a ratio of the heat losses to the quantity of heat supplied to the DH network. In addition, the efficiency of the collective distribution system have been defined in a similar way by means of the ratio of the heat demand at customer level to the quantity of heat supplied to the collective heat distribution network. Figure 6 displays the results of these two performance indicators for each alternative investigated. Both graphics are equivalents and can be used to evaluate in a reliable and comprehensive way the energy performance of collective heat distribution systems. Finally, result denotes that when using local temperature controls strategy for recirculation, a modest improvement can be achieved. For substations without storage tank, when local temperature controls strategy for recirculation are used, the efficiency of the collective heat distribution system increases from *0.82* to *0.86*.

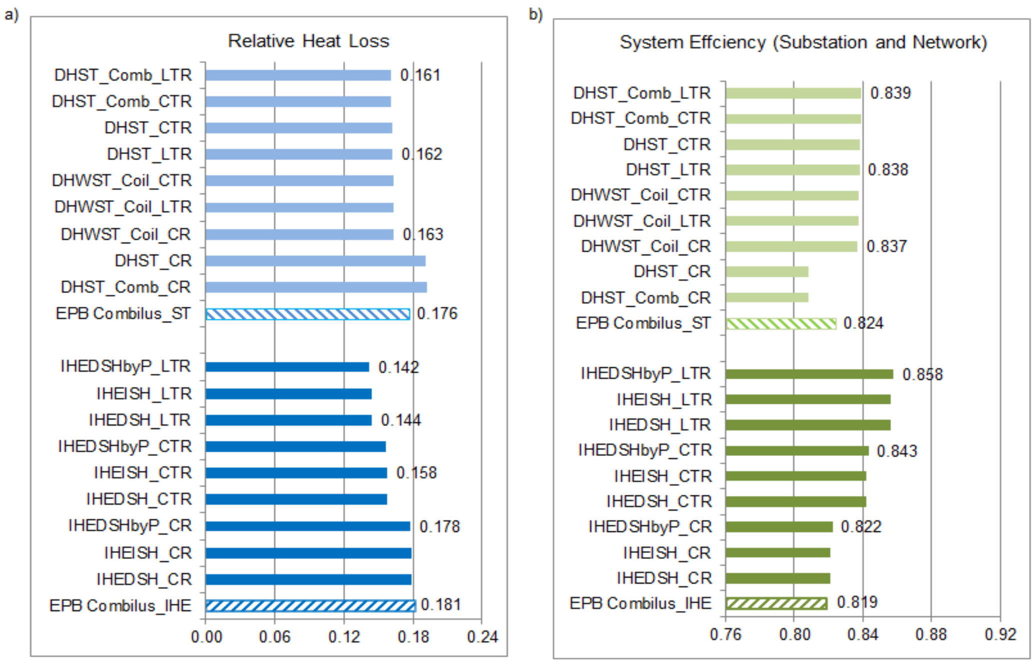

Figure 6. The relative heat loss factor an efficiency of the distribution system of each variants

CONCLUSION

The influence of different recirculation control strategies in collective heat distribution system on the performance of dwelling heating substations and network heat losses was investigated. By means of dynamic simulation, the performance of six different substation types was studied. It was found that when continuous recirculation control strategy is used, the six analysed substations present values of average return temperature above of the *55°C*. When considering the different recirculation scenarios and substation configurations, seven cases were identified which presents better preforms with average return temperatures below *42 °C*. In substations without storage tank, at customer level the return temperatures during domestic hot water generation are on average *23°C* and vary between *21°C* and *31°C*. The average return temperature of domestic hot water of substation with storage tank without bypass to the SH circuit reach values up to *32°C*. It have been demonstrated that all substations warrantee a supply temperature of domestic hot water delivery at the tap above of the 50 °C. As expected, when a continuous recirculation control was used, for all of the studied cases, the monthly average return temperature at plant level reminds above of the *52°C* during the whole year. Substation with bypass in the SH circuit and without heat exchanger in the SH (IEHDHS) presents the best performance in term of return temperatures with values at the central plant of around *33°C* in winter and *38°C* in summer. in systems with substation with storage tank and recirculation control strategy based on CTR and/or LTR, the monthly average return temperatures at the central plant reach value around *28°C* in winter and *35°C* in summer.
When local and/or centralized temperature controls of recirculation is used, the differences between the heat losses in system with substations without storage tank and the ones with storage tank remind somewhat about 10%. According to the monthly heat losses in CHDS when substations with instantaneous preparation of DHW are used, three categories can be defined in correspondence with the recirculation control strategy. For the case of substation with DHW in the storage tank there is no significant impact of the type recirculation control strategy in the level of monthly heat losses of the distribution system. However, those substations with storage tank in the primary side circuit can be separated in two categories. One group can be defined for the cases of both local temperature and central temperature control strategies of the recirculation, while an apart group have to be defined for the case of continuous recirculation. Finally, when using local temperature controls strategy for recirculation in heat distribution system with substations without storage tank results denote that a modest increases from *0.82* to *0.86* in the efficiency of the CHDS can be achieved.

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