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Pipe Internal Recirculation in Storage Connections – An Underrated Problem

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Abstract

Basically, pipe internal recirculation (PIR) at storage connections is a known phenomenon. However, it is not sufficiently considered by storage manufacturers and installers. There is still a lack of awareness and quantification of the PIR effect in typical installations and practice-oriented solutions.

Within this paper, the final results of a research project aiming at the detailed qualitative description and quantification of the effect including extrapolation of the results regarding the PIR impact on storage heat losses are presented. This includes the results regarding the influence of the pipe's material (copper, stainless steel, plastic), diameter, insulation and connection type (direct to storage, indirect via immersed or external heat exchanger) on PIR including their effects on the overall heat losses of ready installed storage tanks. Derived from generalized measurements, a calculation method has been developed, which enables to determine the annual heat losses caused by PIR in domestic hot water storages using dynamic system simulations (TRNSYS). In conclusion, different measures for the reduction of PIR induced heat losses and their effectiveness may be presented.

1. Introduction

Pipe internal recirculation (PIR) in storage connection pipes is a known phenomenon (Suter, 2001) which has been evaluated in different projects (e.g. Andersen, 2007; Huhn, 2007; SPF, 2011). Anyway, many questions still remained unanswered and the issue is not considered enough by installers and manufacturers. In order to find answers to some of the most important questions with regard to typical and practice-oriented storage connections, ISFH has carried one preliminary study supported by the proKlima – Der enercitiy Fonds, Hannover ,(Steinweg, 2012), followed by research project founded by the Deutsche Bundesstiftung Umwelt The aim was to work out and to evaluate the different influences on the development of PIR. Furthermore, different PIR reducing measures have been tested according to their effectiveness and, using this information, optimal guidelines for minimizing PIR losses have been derived. On the one hand, connection pieces for the integration between heated elements and connection pipes like back flow preventers, convection brakes or heat traps (pipe pieces in U- and Z- shape) and on the other hand measures designed by manufacturers like slanted storage connections have been tested. On the basis of the collected database, a model realized for dynamic system simulations in TRNSYS has been developed, which enables the determination of the dynamic heat losses caused by PIR in storage connections for typical installations (Steinweg, 2014a). Associated to that, recent outcomes have been spread to installers and manufacturers by presentations and workshops to discuss practical aspects in expert's workshops. This paper summarizes the most important research outcomes and the project conclusions.

2. Development of PIR

PIR develops with increasing temperature difference between the fluid of the storage tank and the content of the connected pipe. This happens for example after the end of a hot water drawing because the pipe content

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cools, due to the higher surface to volume ratio, much faster than the storage fluid which is nonetheless often kept on high temperatures by an auxiliary heater. With the increasing temperature difference the density difference between warmer, lighter water of the storage and colder, heavier water in the pipe increases, too. The cold water of the pipe is not in equilibrium and therefore is submitted to an increasing force to sink below the hot water in the storage. Therefore it begins to “fall” towards the storage bottom. To keep the mass balance, hot storage water begins to flow into the pipe in equal measure. The warm forward flow spreads along the axis of the pipe while cooling down slowly and then closes the circulating flow inside the pipe by turning back into the storage as cold backward flow. A circulating pipe internal flow with wide spread continuously draws heat out of the storage. A detailed analysis of the development process of PIR can be found in (Steinweg, 2014a).

3. Results of the measurements

3.1 Determination of PIR induced heat losses

The circulation flow which spreads inside the connection pipe generates a characteristic temperature profile inside the pipe. The heat losses of a pipe connected to a customary thermal storage tank are determined using the axial temperature distribution of the pipe, which is measured accurately by up to 50 temperature sensors. The mean pipe temperature is used to calculate the heat losses of the pipe arrangement using the pipes specific heat loss coefficient and the effective temperature difference between mean pipe and ambient temperature. By dividing the heat loss rate at fully developed PIR in steady state conditions by the difference of storage and ambient temperature, the heat loss coefficient of the arrangement $(UA)_k$ in W/K can be calculated. This heat loss coefficient is the essential parameter for the evaluation of the considered connections and is subsequently used as characteristic value. In connection with a sophisticated test method the heat loss coefficient has been determined with an uncertainty below 0.02 W/K. It furthermore can be summed with further heat loss coefficients e.g. the storage heat losses according to its test report. A more detailed description of the experimental and evaluation method is explained in (Steinweg, 2014a).

3.2 Influence of the pipe material

For evaluating the influences of the pipe material the PIR induced heat losses have been measured for Cu-, CrNi- and plastic pipes. Figure 1 displays the increase of the $(UA)_k$ value caused by stainless steel and PEX (polymerized polyethylene) compared to a copper reference pipe with equal inner diameter at three different pipe temperatures.

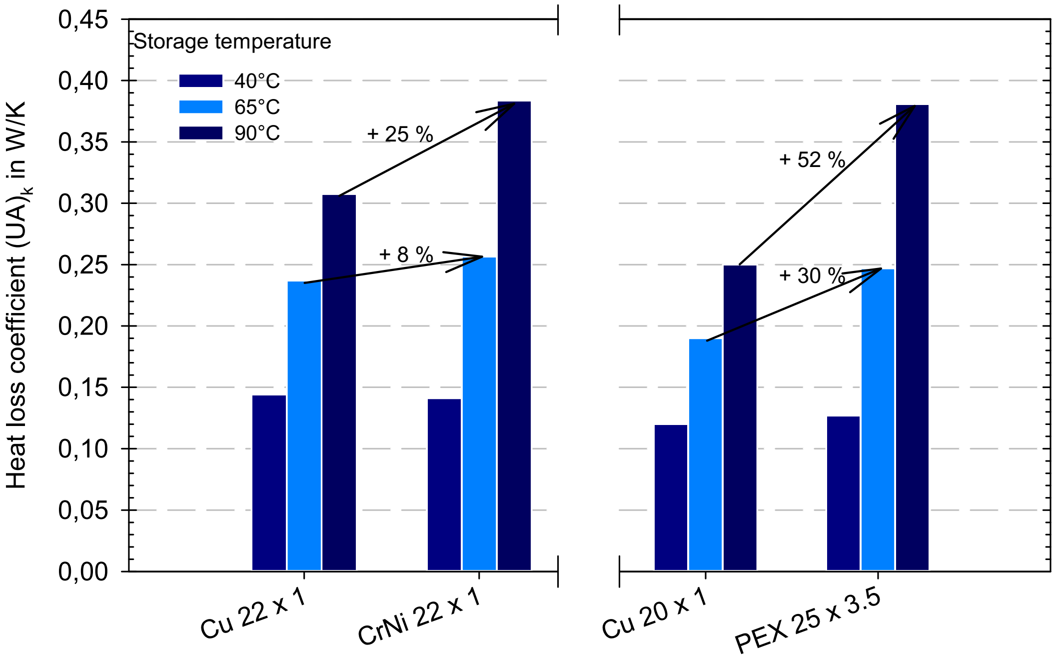

Figure 1: Increase of PIR induced heat losses for CrNi- and PEX- pipes compared to a Cu pipe with equal inner diameter for three different storage temperatures (all pipes orientated horizontal, 6,5 m length, 25 mm insulation)

It displays that the increase of the heat loss coefficient is higher if storage temperatures rise or the thermal conductivity of the pipe material sinks. The reason for this is the influence of these parameters on the temperature difference between warm forward and cold backward flow inside the connection pipe as driving force of PIR. High storage temperatures increase this temperature difference. Moreover, low thermal conductivity of the pipe material reduces the tangential heat conduction inside the pipe's wall which supports the vertical temperature stratification in the pipe's fluid and thereby stabilizes and thus amplifies the PIR flow. The experiments show, that the temperature difference between upper and lower surface of the pipe is far more pronounced than at a copper pipe. This leads to a larger spread of the circulation flow inside the pipe and thus to higher PIR heat losses (Kliem, 2013), if low conductivity materials are used. As a result, the utilization of PIR reducing measures becomes even more important if pipe materials with low thermal conductivity are deployed.

3.3 Influence of the pipe diameter

For evaluating the influence of different pipe diameters the *(UA)ₖ* values of five copper pipes, each with the same wall thickness but varying inner diameters between 10 mm to 26 mm have been measured. The left diagram of Figure 2 displays the results for three different storage temperatures. The thermal resistance of the pipe insulation has been kept constant for all diameters.

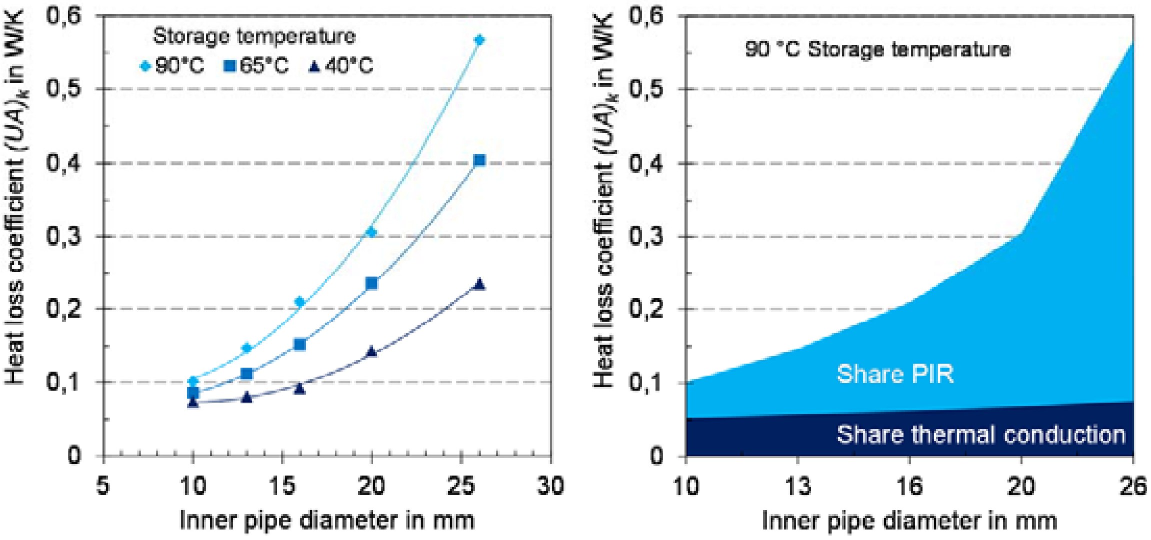

Figure 2: Heat loss coefficient *(UA)ₖ* of horizontally connected Cu pipes with different diameters, wall thickness 1 mm, length 6.5 m. Left: *(UA)ₖ* values at different storage temperatures. Right: *(UA)ₖ* values as function of pipe diameter with calculated share of pure thermal conduction via pipe material and water (cooling fin effect), storage temperature 90 °C.

The diagram on the left clearly shows the high impact of the pipe diameter on PIR losses. Starting from the reference pipe with 22x1 mm (20 mm inner diameter) a diameter enlargement of 6 mm (28x1 mm, 26 mm inner diameter) results in a nearly doubled *(UA)ₖ* value. Since larger pipe diameters have a much lower hydraulic resistance, the measured spread of circulation flow inside the pipe extends. Supporting that, the (counteracting) tangential heat conduction lowers its influence due to larger pipe diameters. Smaller pipe diameters however lead to lower PIR losses as a consequence of the decreasing spread of circulation flow due to higher hydraulic resistances and increasing influence of tangential heat conduction.

The diagram on the right of Figure 2 displays *(UA)ₖ* value shares at a storage temperature of 90 °C. A basic amount of the overall PIR losses is caused by the cooling fin effect of the pipe connected to the storage – these losses are solely caused by thermal conduction inside the pipe's wall and fluid. They may also be found without PIR and lead to continuous storage heat losses. The second fraction is caused only by PIR. This illustration reveals that for the reference case (22x1 mm pipe, 20 mm inner diameter) the share of PIR induced heat losses makes up more than 75 % of the overall losses. The share of losses due to longitudinal or axial heat conduction increases with lower pipe diameters and dominates the overall heat losses at smaller diameters or lower storage temperatures. Both diagrams clarify that even without PIR reducing measures the choice of small pipe diameters contributes significantly to a reduction of PIR induced heat losses of a configuration. Furthermore, there exists a lower limitation given by thermal conductivity within pipe and fluid. This limitation may be lowered further by choosing pipe materials with low thermal conductivity.

3.4 Impact of the connection type

Within a further measurement the impact of different storage connection types on PIR losses has been evaluated. The resulting $(UA)_k$ values are given in Figure 3. Besides the results of direct connected pipes, an internal heat exchanger (“int. HX”) and an exemplarily installed external heat exchanger of a solar heat transfer module (“ext. HX”) are included. Since the external heat exchanger aroused both PIR (“only PIR”) and circumferential circulating fluid flow between heat transfer module and storage (“circ. circulation”), there are heat loss coefficients given for both cases. Additionally, the impact of imperfect insulation at the storage connector has been measured and is also given below. Hence, a pipe segment of 100 mm remained uninsulated (“100 mm ins. missing”).

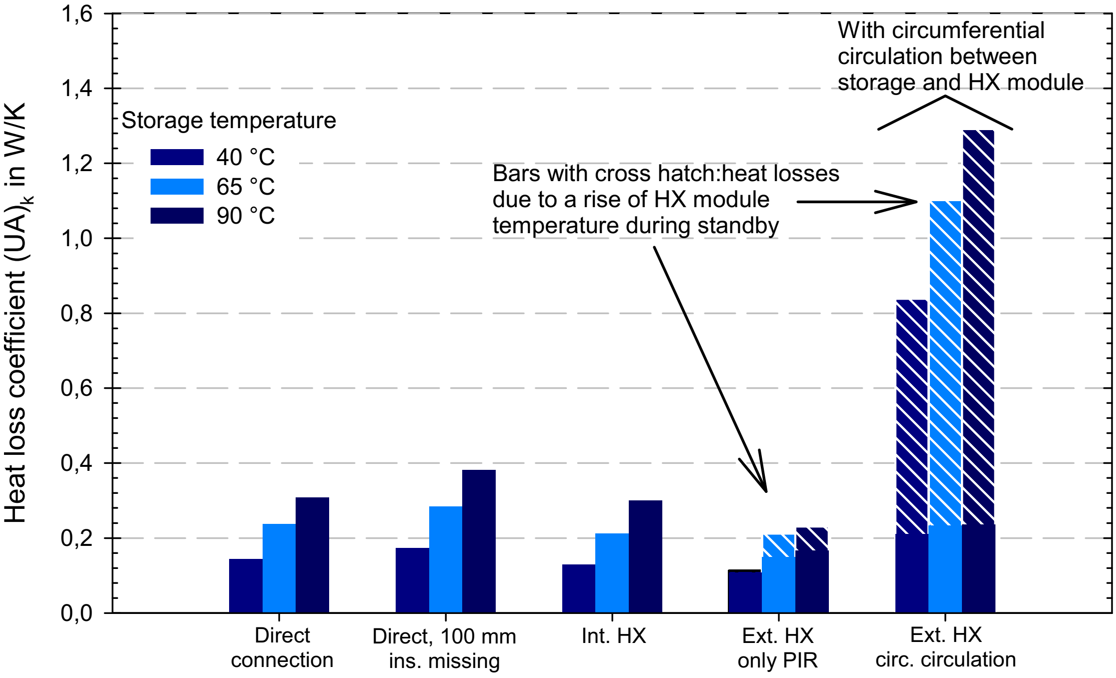

Figure 3: Heat loss coefficients for different storage connection variants and storage temperatures of 40 °C, 65 °C and 90 °C.

Direct connection, internal heat exchanger and pipe with imperfect insulation measured with a 22x1 mm Cu pipe, horizontal orientation, length 6.5 m, 25 mm insulation.

External heat exchanger as part of a solar heat transfer module with two storage connections: length supply pipe (HX to storage) 0.93 m, length return pipe 1.96 m, 22x1 mm Cu pipe, 25 mm insulation, secondary circuit of heat exchanger emulated with uninsulated pipe loop, in all cases related to single pipe connection

The missing insulation at the storage connection, a deficit which may frequently be observed, increases the local heat losses dramatically. Though, it does not reduce the spread of PIR, the temperature profile remains unchanged. Therefore, the heat losses rise significantly.

The consideration of the heat loss coefficients of the internal spiral tube heat exchanger connection clarifies that measures inside the storage tank do not influence PIR heat losses. Although a direct exchange of fluid between storage and pipe is not possible, the thermal contact between the two fluid circuits is sufficiently intensive for developing nearly the same PIR losses.. Therefore, it is quiet unlikely that any measures implemented inside the storage volume like e.g. upwards bended pipe outlets lead to an efficient PIR reduction.

The heat loss coefficients of a single pipe at the external heat exchanger appear to be low in case of exclusively occurring PIR. Nonetheless, for a representative comparison they need to be doubled since external heat exchangers are always coupled using two pipes. Furthermore, it has to be considered that the length of the connection pipes are about one and two meters, respectively, while PIR spreads especially at high temperatures far beyond that. Moreover, especially at high storage temperatures or with occurring circumferential circulation in the storage connection circuit of the heat exchanger a considerable warming of the solar heat exchanger module occurs. The hereby additionally resulting heat losses at the modules surface (shown as cross hatch bar parts in the diagram) increase the heat losses significantly to 1.3 W/K per connection pipe which corresponds to 2.6 W/K for the whole arrangement.

Measures for PIR reduction

For the evaluation of the effectiveness of different PIR reducing measures, these parts have been inserted between storage connector and a horizontal copper reference pipe (22 x 1 mm) and tested. Their PIR induced heat losses have been determined. The effectiveness of some extracted measures may be compared in Figure 4. The diagram shows the PIR induced heat loss coefficients of each measure for three different storage temperatures. The following assessment distinguishes “recommended measures”, “still satisfying measures” and “inadequate measures”.

- Recommended measures

The test results allow the conclusion that copper heat traps or Z- profiles with long downward orientated side lengths and inclined storage connectors show good results. The downwards oriented side length of the copper heat traps should at least be 13 times the inner pipe diameter, due to the high longitudinal heat conduction. The 45 ° sloped storage connectors made of steel (placed within the storage insulation) appears to be acceptable with six times the inner pipe diameter. Nonetheless, the effort to properly install the insulation material around the sloped pipe is higher an additional thermal bridge effect has to be expected. Best effectiveness is achieved by heat traps made of CrNi steel pipes (also corrugated pipes) whereas these may be designed with remarkably shorter downward side lengths. In this case, six times the inner pipe diameter can be recommended as well. Because of their compact size they can be considered as the most effective solution.

- Still satisfying measures

Short copper heat traps and convection breaks achieve still satisfying heat loss coefficients. Their use may be justified at arrangements, where a lack of installation space or material choice leaves no alternatives.

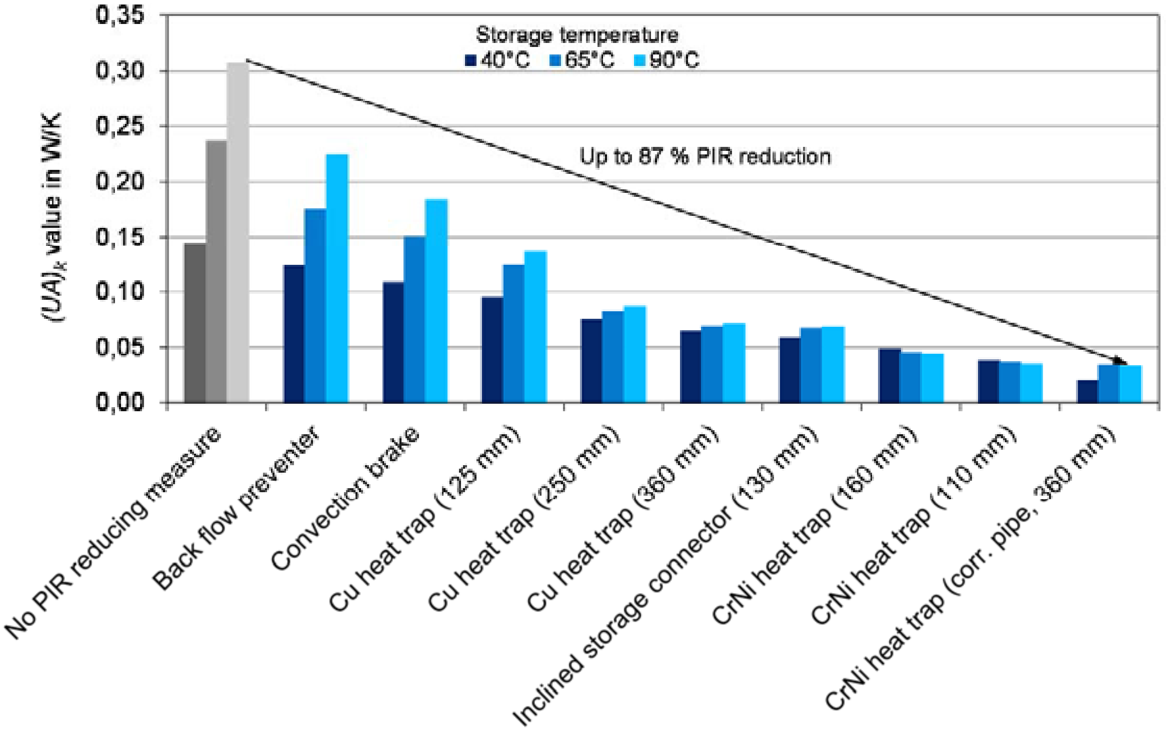

Figure 4: *(UA)$_k$* values of different PIR reducing measures. Measurement with connected Cu pipe, 22x1 mm, horizontal orientation, length 6.5 m, 25 mm insulation, storage temperature 40 °C, 65 °C and 90 °C.

- Inadequate measures

Back flow preventers do only reduce PIR losses to a low extent, when being at full function. Their moving parts however have a high risk of malfunction, i.e. they may not close properly.. In that case no PIR reduction effect has been measured. Furthermore, all measures that are placed inside the storage volume are considered to be inadequate if the heat transfer between tank water and tube water is not avoided.

4. Annual PIR induced heat losses of a domestic hot water (DHW) system

With help of a simulation study in TRNSYS, the annual PIR induced heat losses of a typical solar DHW system with 7 m² collector area and 370 l storage volume have been evaluated. For that purpose, a model for the non-steady state calculation of PIR induced heat losses has been developed and implemented as TRNSYS type. Based on the simulation model of EN 12977-2 (Deutsches Institut für Normung e.V, 2012) for the forecast of the long term behavior of custom build solar collector systems the PIR model has been implemented. Further information is given in (Steinweg, 2014b).

The following Figure 5 summarizes the annual heat losses due to PIR and pipe cooling of the DHW system's storage connection pipes for two different DHW demand profiles. On the one hand a profile with a single draw off per day, based on EN 12977-2, and on the other hand a profile with about 23 draw offs per day with different mass flow rates, based on the IEA SHC Task 44 (Haller et.al., 2012). Both profiles remove 200 l/d at 45 °C from the tank, resulting in an end energy demand of about 2025 kWh/a.). It has to be noted, that all calculations have been carried out under ideal conditions, no circumferential flow and perfect insulation according to German regulations have been considered.

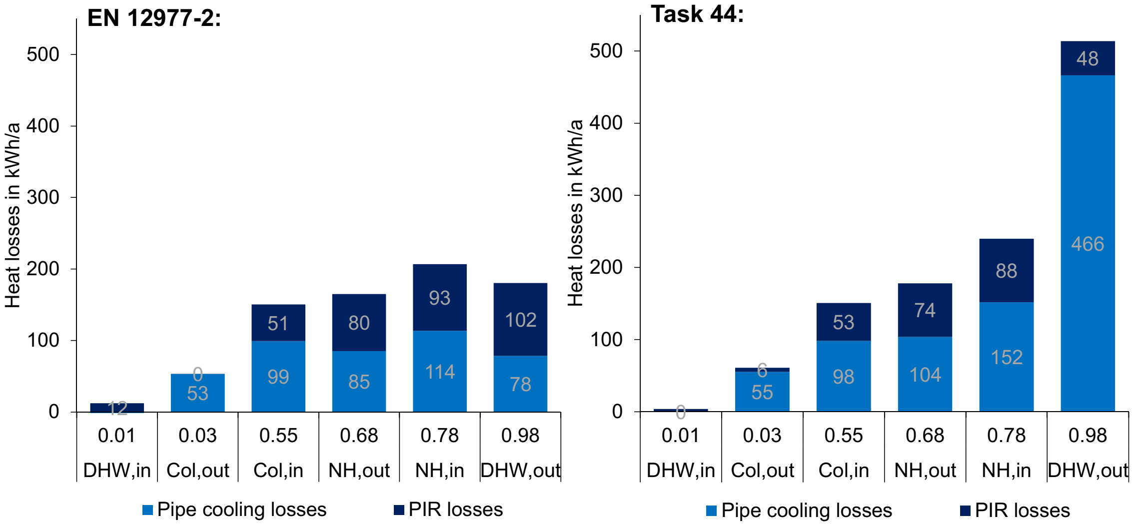

Figure 5: Overview of the annual heat losses of the connection pipes of a solar DHW storage for DHW profiles based on EN 12977-2 (left) and IEA SHC Task 44 (right).

DHW: connection pipes for domestic hot water, Col: connection pipes for thermal collector, NH: connection of the auxiliary heater, in: inlet connection pipe, out: outlet connection pipe, the numbers given on the x axis are relative connection heights

Depending on the DHW demand profiles the pipe losses are separated into PIR losses and the instantaneous cooling down of the pipe (capacity loss). The latter are almost inevitable but may be minimized by choosing the smallest pipe diameter possible. The annual PIR induced heat losses account for between 270 kWh/a (Task 44) and 340 kWh/a (EN 12977-2).

The developing PIR increases the storage heat losses by 30 % to 40 %. These losses mainly appear within the auxiliary heating zone due to the position of the storage connections and need to be covered mainly by the auxiliary heater. That's why the end energy demand of the auxiliary heater increases about 20 % to 25 %. For this example, it resembles an annual increase of fuel costs of approximately 30 €/a.

The PIR induced heat losses account up to 100 kWh/a per storage connection. Hence, the duration of the standby period and the mean storage temperature at the storage connection layer is of most importance. The longer the time without water draw, the higher the share of PIR induced heat losses.

Consequently, PIR reducing measures for storage connections within the auxiliary heating zone are extraordinary profitable and highly recommended.

The PIR induced heat losses are independent of the quality of insulation and of the storage volume. Accordingly, PIR losses have – in relative terms –a massive impact on storage tanks with small volume and high quality insulation.

An equivalent study for a solar combi storage reveals, due to the higher amount of storage connections, annual heat losses of 340 kWh/a (Task 44) to 400 kWh/a (EN 12977-2

5. Conclusions

The results of the described evaluations of PIR induced heat losses at a typical storage installation identify the mechanisms which drive the development of PIR in pipe connections and the different parameters that influence the amount of PIR induced heat losses. In particular, PIR losses become higher if pipe materials with low thermal conductivity are used. The pipe diameter as well significantly influences the absolute value of PIR induced heat losses. A diameter change from 22x1 to 28x1 nearly doubles the PIR losses. Anyway, the smaller the pipe diameter the higher will be the share of heat losses caused by heat conduction inside the pipe walls (cooling fin effect).

Neither the omission of a section of the pipe insulation nor the existence of internal or external heat exchangers leads to a reduction of PIR induced heat losses. Especially when using external heat exchangers, PIR losses may provoke circumferential circulation flow between the storage and heat exchanger connections resulting in far higher heat losses. This is of extraordinary importance especially for the installation of fresh water modules at the upper hot zone of the storage.

Although pipe materials with low thermal conductivity show higher losses when installed horizontally, they are excellent in order to minimize PIR induced heat losses when used as material for heat traps in U- or Z-shape. Even with short downward side lengths they have a high effect. While copper as pipe material requires downwards oriented side lengths of at least 13 times the inner pipe diameter, CrNi steel, PEX or other plastics only require six times the inner pipe diameter. Downwards sloped pipe connectors welded on the tank mantle as a manufacturer measure also may be recommended for effective PIR reduction.

On the basis of the collected measurement data, especially the numerous time dependent temperature profiles along the reference pipes, a calculation method for the development of PIR induced heat losses at storage connections has been established. This method has been implemented in a simulation model which enables the dynamic calculation of the annual heat losses of typical (solar assisted) heating systems. The identified energy savings of about 300 kWh/a point out that easy to establish and highly cost effective PIR reducing measures like heat traps already depreciate in short terms. This is especially valid for new installations.

Finally, PIR may not only be found at connections between thermal storage tanks and the pipe installation but also at other components which are often kept on higher temperature levels than the ambient temperature, like boilers, manifolds, and others. Thus, the relevance of PIR caused heat losses may be considered as an important efficiency potential, which may easily be made accessible.

6. Acknowledgements

The project outcomes have been published within a booklet entitled “Wärmeverluste durch Einrohrzirkulation – Bewerten und Vermindern” (ISBN 978-3-9816770-0-3, written in German language). The digital document can be ordered from the main author.

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