Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 48 (2014) 664 – 673

Energy Procedia

SHC 2013, International Conference on Solar Heating and Cooling for Buildings and Industry
September 23-25, 2013, Freiburg, Germany

Pipe internal recirculation in storage connections – Characteristics and influencing parameters

Jan Steinweg[a]*, Francis Kliem[a], Gunter Rockendorf[a]

[a]*Institut für Solarenergieforschung Hameln/Emmerthal, Am Ohrberg 1, 31860 Emmerthal, Germany*

Abstract

Pipe internal recirculation (PIR) is an undesired phenomenon which may lead to significant additional heat losses. Although different research institutes already measured singular PIR effects, there is still a lack of wide-ranging evaluations and practical solutions.
This paper describes a test and evaluation method and reports on results regarding the influence of the pipe´s slope, the material (copper, stainless steel) and diameter on the PIR caused heat loss coefficient. For combined pipe path arrangements a new method is presented, which allows to calculate the heat losses from basic investigations on horizontal and vertical pipe orientations. This method has been experimentally validated. Finally, the effectiveness of different measures for the reduction of PIR induced heat losses is presented.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: thermal storage, heat losses, pipe internal recirculation, pipe connection, heat trap, micro-circulation

1. Introduction and motivation

For evaluating the thermal losses of heat storages its transmission heat losses, which essentially can be reduced by an appropriate insulation, are mostly considered. Besides these there are several further criterions which increase heat losses like thermal bridges at unused and insufficiently insulated pipe connections or immersion sensor sleeves

* Corresponding author. Tel.: +49 (0)5151 999-645; fax: +49 (0)5151 999 500.
E-mail address: steinweg@isfh.de

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG
doi:10.1016/j.egypro.2014.02.077

on the storages steel surface. Furthermore, storage losses can be increased substantially by the so-called pipe internal recirculation (PIR) emerging at storage connections with connected pipes. This phenomenon is currently not sufficiently rated by relevant standards (e.g. DIN EN 15332, DIN EN 12977-3/-4) since they evaluate the storage in a test facility with a minimum of (ideally) connected pipes. Consequently, the gained product data resembles an idealized installation; installations customary in practice may lead to significantly higher heat losses.

Nomenclature

α_a	Convective and radiative heat transfer coefficient from outer pipe surface to surrounding space in W/(m²K)
d_a	Pipe diameter outside the insulation in m
d_i	Pipe diameter inside the insulation in m
λ_D	Thermal conductivity of the pipe insulation in W/(mK)
$\dot{Q}_L$	Heat losses of the test pipe in W
$T_{P,i}$	Mean test pipe temperature in in segment i in °C
T_{amb}	Ambient temperature in °C
T_{St}	Storage temperature at connecting piece in °C
$U_{L,R}$	Heat loss coefficient of the test pipe with insulation in W/(mK)
$(UA)_k$	Storage tank related heat loss coefficient, caused by connected test pipe, in W/K
x_i	Length of the test pipe segment i in m

PIR in storage connection pipes is a long known phenomenon [1] which has been measured in different research studies (e.g. [2], [3] and [4]). Anyway, numerous questions remain open and the consequences of PIR are not considered sufficiently in practice. Some of the most essential questions regarding typical storage connection configurations like the magnitude of the PIR caused additional thermal losses, their determining parameters and how to measure them precisely have already been answered at ISFH within a research project funded by proKlima – Der enerctiy Fonds, Hannover. Furthermore, different measures for the reduction of PIR have been tested, compared and evaluated [5].

Within a research project supported by the "Deutsche Bundesstiftung Umwelt (DBU)" the analysis goes further: The goal of this project is to gain comprehensive insights and results which may preferably be generalized. The work covers

- the measurement of a broad number of storage connection variants, considering different pipe diameters, pipe materials and pipe inclinations,
- the evaluation of the impact of PIR reducing heat traps or Z-profiles as well as different measures of storage manufacturers like inclined connecting pieces and others,
- the derivation of an easy to apply calculation method basing on existing measurements for the prediction of PIR caused heat losses in an arbitrarily combined sequence of pipe segments as well as the estimation of the annual PIR induced storage heat losses using an appropriately modified dynamic system simulation.
- Finally, all findings will be spread to storage manufacturers, distributors and installers by trainings and workshops.

The following paper explains the test facility including its recent improvements. As results, both the dependency of the pipe's inclination and the influence of the pipe's diameter on PIR losses will be presented. Furthermore, PIR induced heat losses of more complex sequential pipe arrangements will be analyzed and compared.

1.1. PIR as undesired flow – development

If a desired flow of hot water via a connected pipe (e.g. heating of a storage tank or tapping of hot water) is stopped, the pipe cools down much faster than the storage tank. Cold water in the pipe is now directly facing the hot water in the tank. A driving force caused by the density difference leads to a beginning flow. Thereby, the cold water of the pipe "falls" down to the storage tank bottom, while – preserving the mass balance – hot water flows out of the storage tank into the pipe. This PIR may expand inside the pipe and spread over large distances. Thus, heat from the tank is dissipated in the pipe, leading to an additional cooling of the storage tank.

Shut-off devices can influence the process of PIR between storage and pipe (see Fig. 1). If a valve interrupts the pipe flow near the storage entry, heat is transferred via conduction from storage to pipe. PIR then can be found on both sides of the valve, a direct transfer of storage water does not occur. The thermal storage is cooled in a similar and nonetheless significant way. We have shown that a good working backflow preventer only reduces the PIR losses by about 10% to 30% [5].

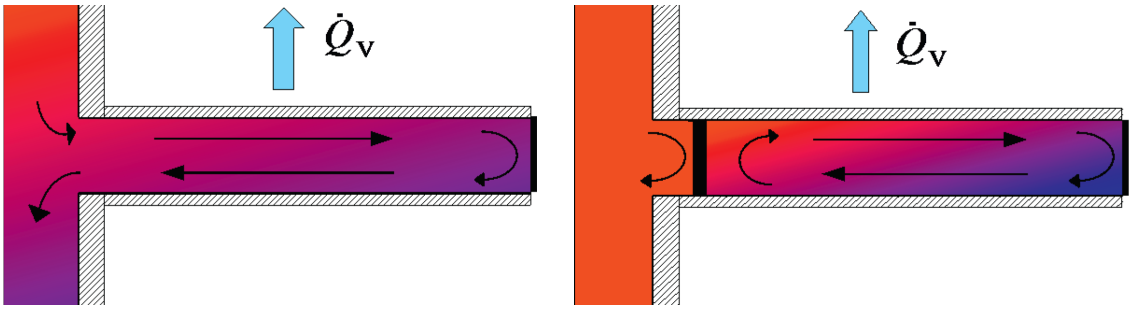

Fig. 1 Scheme of pipe internal recirculation (PIR) with horizontally connected pipe; left without and right with flow preventing valve.

2. Procedure for the determination of PIR losses

A typical thermal heat storage (below 1000 l) shows a heat loss coefficient of about 2 W/K to 5 W/K, additional heat losses caused by PIR inside of only one horizontal pipe connection have been measured within a range of 0.05 W/K to 0.31 W/K. Thus, a significant conclusion requires a maximum uncertainty of about 0.02 W/K. This is the reason, why an evaluation based on the balance of the overall storage heat losses including the connected pipe is inappropriate, because this method leads to far higher uncertainties (above 0.1 W/K).

The test facility for the measurement of thermal losses due to PIR is designed to enable tests of relevant installations. The most important aspect of the measurement procedure is the precise measuring of the test pipe's temperature distribution with fully developed PIR. For this, up to 50 temperature sensors are spread along the pipe on its upper and lower side. The pipe is connected to a common solar combi-storage which is heated to the desired temperatures by a controlled thermostatic module. This enables the precise measurement of the local temperature distribution along the test pipe with PIR – beginning with its development and ending up with the steady state temperature profile. All tests are carried out under the condition that the installation of the pipe and storage insulation has been done with most diligence and according to the approved state of the art. A more detailed description of the test facility can be found in [5].

2.1. Evaluation

The heat losses of the connected pipe are determined using the measured temperature distribution along the pipe's length. Thereby, it is assumed that the temperature of a pipe segment $T_{P,i}$ correlates with the heat losses $Q_{L,i}$ of the segment i with the length x_i following Eq. (1):

$$\dot{Q}_{L,i} = U_{L,R} \cdot x_i \cdot (T_{P,i} - T_{amb}) \tag{1}$$

The heat loss coefficient $U_{L,R}$ in Eq.(2) is calculated in W/K per meter pipe length. For a copper pipe with 22 mm outer diameter and an insulation with 25 mm wall thickness and a thermal conductivity of 0.04 W/(mK) a material specific value of 0.19 W/(mK) is calculated.

$$\frac{1}{U_{L,R}} = \left(\frac{1}{2 \cdot \lambda_D} \cdot \ln \frac{d_a}{d_i} + \frac{1}{\alpha_a \cdot d_a} \right) \frac{1}{\pi} \qquad (2)$$

The heat losses Q_L in W are calculated using the measured temperature distribution (see Eq. (1)). As the temperatures along the pipe and with that the heat losses Q_L for the configuration k are depending on the driving temperature difference between heat storage T_{St} and ambient air T_{amb}, a storage tank related heat loss coefficient $(UA)_k$ for this connection configuration can be calculated.

$$(UA)_k = \frac{\dot{Q}_{L,k}}{(T_{St} - T_{amb})} \qquad (3)$$

This heat loss coefficient is the main parameter for the evaluation of a storage connection. The loss coefficients of all tank connections may be summarized, and then be added to further loss coefficients and the original loss coefficient of the storage tank data sheet. This way, an overall heat loss coefficient of the installed storage may be calculated.

2.2. Improvements of the test facility

Based on the experiences of the previous measurements [5] some changes of the test facility have been implemented. Thus, the measurement accuracy has been improved regarding further more detailed issues.

Up to now, the test pipe has been fixed with four common pipe clamps (outside the pipes insulation). This simple fixation relates to customary practice but cannot assure a constant pipe orientation for the whole test pipe length. As particularly measurements show a severe impact of the pipe's inclination (see chapter 3.1) on the PIR losses a rectangular aluminum profile carrying the pipe on full length has been used to replace the clamps. With this arrangement and use of a sophisticated angle measurement the test pipe adjustment shows an uncertainty of 0.1°.

The facility has furthermore been equipped with movable walls which surround the test pipe. One the one hand they serve as protection against unwanted exchange of radiation between the test pipe and its surrounding. One the other hand they reduce convective air flows near the pipes surface caused by the laboratories air conditioning system to a natural amount. Finally, some additional pipe connections have been added to the thermal storage (inclined connector and connector on the storage top). In case of an horizontal pipe connection, the length of the test pipe has been increased to about 6.5 m. Fig. 2 shows the test facility at its recent status.

Fig. 2: Left: Test facility with improvements like the the continuous aluminium profile for exact adjustment of the test pipe (correct to 0.1°); Right: Test facility with a combination of a vertical and a horizontal pipe segment connected to the storage connector on top. The picture shows test pipe setup (B) according to chapter 3.5.

3. Description of recent results

In this chapter, the following aspects will be discussed:

- Dependency of PIR on the pipe's inclination, with different pipe materials
- Influence of the pipe diameter on PIR
- A new procedure for the measurement and prediction of PIR induced heat losses in combined vertical and horizontal pipe segments
- The effectiveness of some measures for the reduction of PIR

3.1. Impact of the pipe slope on PIR

The left graph of Fig. 3 compares steady state temperature profiles at 90 °C storage temperature for a slight change of the test pipes inclination while the graph on the right displays the influence of major changes of the inclination angle compared to horizontal pipe installation. The diagrams display the pipe temperatures vs. the distance from the storage connecting piece.

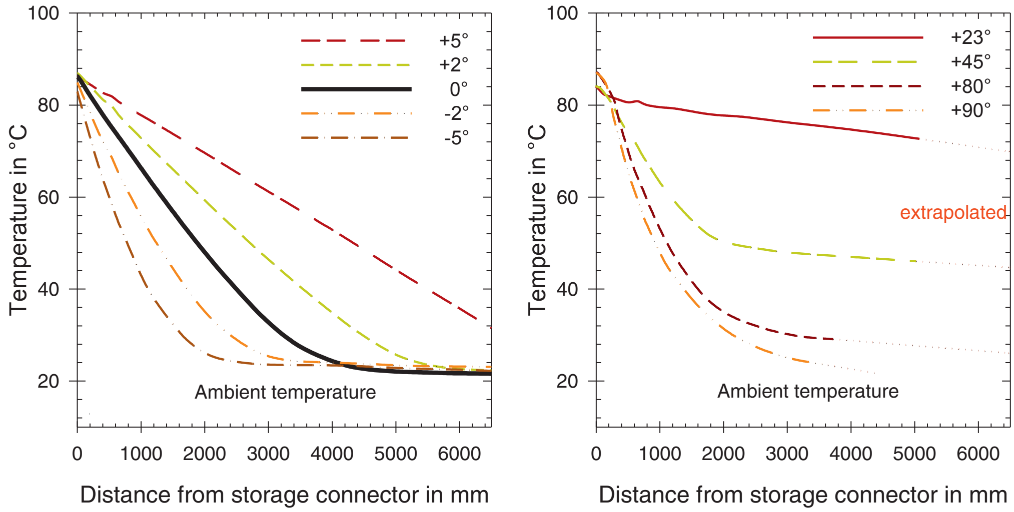

Fig. 3: Steady state temperature profiles for slight (left) and big (right) changes of the inclination angle of the test pipe (Cu pipe, 22x1 mm, 25 mm insulation, lambda = 0.04 W/(mK), i.e. 100 % insulation according to German EnEV standard), storage temperature 90 °C. Parameter: Inclination angle compared to horizontal installation, positive: the test pipe is installed ascending from the storage connection piece.

It is obvious that the spread of PIR significantly increases with only slight positive inclination angles while negative inclinations decrease the spread. Furthermore, the spread does not increase steadily with rising inclination to the point of vertical pipe orientation. Up to an angle of 23° PIR reinforces with a remarkable linear temperature profile. This indicates a constantly high flow velocity along the entire considered test pipe range. At an inclination angle of 45° a combination of a curved (up to about 2 m) and a linear temperature profile occurs. It is therefore assumed that in the first part of the test pipe, close to the storage connecting piece, no characteristic two-zone counterflow develops due to a turbulent mixing of the opposed flows. This effect is comparable to flows in vertical pipes described in [6]. After a certain temperature drop the amount of mixing decreases until the separated two-zone flow, typically for horizontal pipe orientation, develops. The characteristic of the temperature profile at an inclination angle of 80° remains similar to the perfectly vertical orientated pipe but with a larger spread of PIR, even larger than the horizontal connection (0°).

3.2. Impact of the pipe material on PIR

The left diagram of Fig. 4 displays temperature profiles for a Cu pipe compared to those of a CrNi pipe for inclination angles of -1°, 0° and +1°. The diagram on the right side of Fig. 4 displays the appropriate temperature differences between upper and lower pipe temperature sensors of the described arrangements. A high temperature difference at low distance indicates that the heat flow in the tube wall from top to bottom is small.

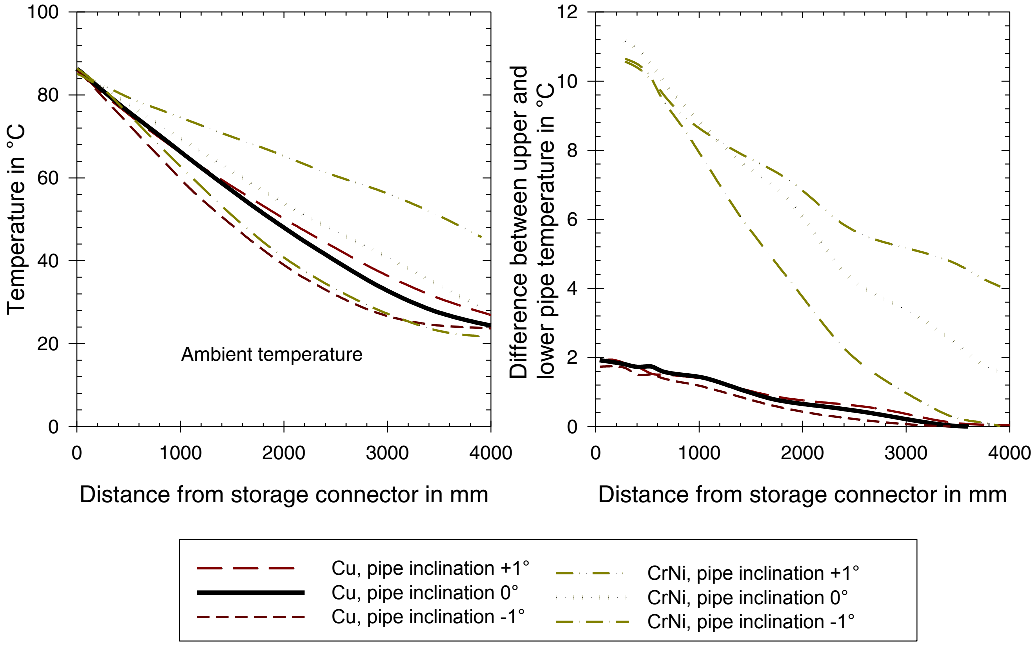

Fig. 4: Left: temperature profile of a Cu pipe compared to a CrNi pipe for inclination angles of -1°, 0° and +1°; right: appropriate temperature differences between upper and lower pipe temperature sensor of the test pipes, storage temperature 90 °C

The intensity of PIR at horizontal orientation is higher in a stainless steel pipe than in a copper pipe, as to be seen in the left diagram. Furthermore, the deviation of the CrNi pipes with +1° and -1° from horizontal installation shows larger effects on the spread of PIR. This is caused by a lower tangential heat conduction of the stainless steel pipe compared to the copper pipe which supports the formation of internal fluid flows due to a more pronounced stratification of cold and warm fluid zones. A comparison of the temperature differences between upper and lower pipe wall (see Fig. 4) confirms this assumption. The temperature differences between upper and lower temperature sensors of the stainless steel pipe show a far higher value compared to the one of the copper pipe.

3.3. Heat loss coefficients for different pipe slopes, materials

Fig. 5 displays the heat loss coefficients of the already discussed test pipe orientations and materials (Cu, CrNi). If the inclination angle of a horizontal pipe (22 mm) is varied by +/- 2°, the loss coefficient changes with both materials by about +50% and -25% respectively. The losses of a CrNi pipe however are about 25% higher than those of a Cu pipe. The heat loss coefficients for inclination angles of more than 5° are based on extrapolated temperature profiles since the spread of PIR was much higher than the overall test pipes length.

Between -5° and +23° inclination the heat loss coefficients are rising and between +45° and +90° (vertical orientation) they fall again. The heat losses of the considered Cu pipe at 90 °C storage temperature have a maximum between +5° and +45°. We assume that it will most likely be between +15° and +35°.

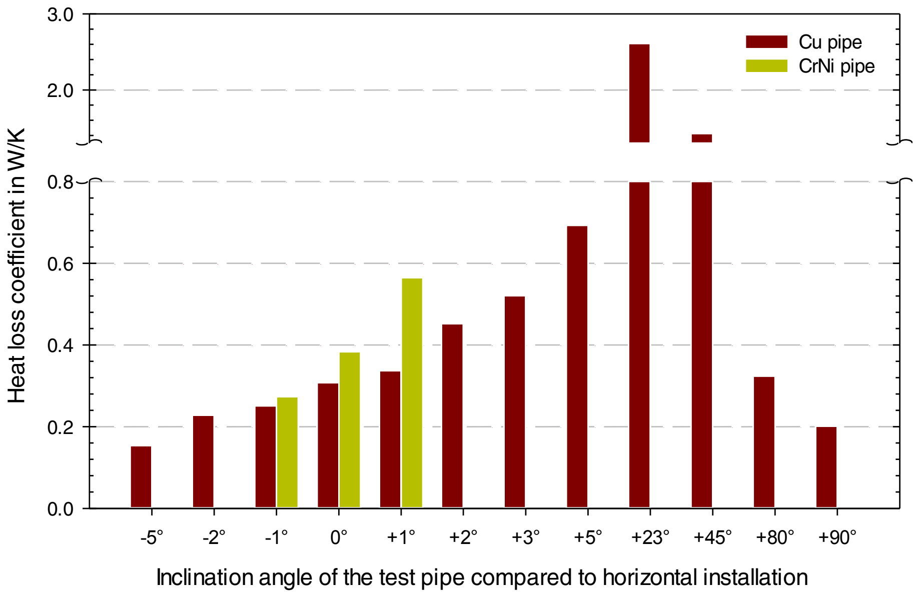

Fig. 5 Heat loss coefficients for different inclination angles compared to horizontal orientation for a copper and a stainless steel pipe (22x1 mm, 25 mm insulation with 0.04 W/(mK), 100% insulation according to EnEV standard), storage temperature 90 °C

3.4. Impact of the pipe diameter

The diagram of Fig. 6 shows the influence of the test pipe's inner diameter on the amount of heat losses caused by PIR for a horizontal Cu pipe with constant pipe wall thickness of 1 mm and storage temperatures of 40 °C, 65 °C and 90 °C. The test pipes inner diameters vary from 10 mm to 26 mm.

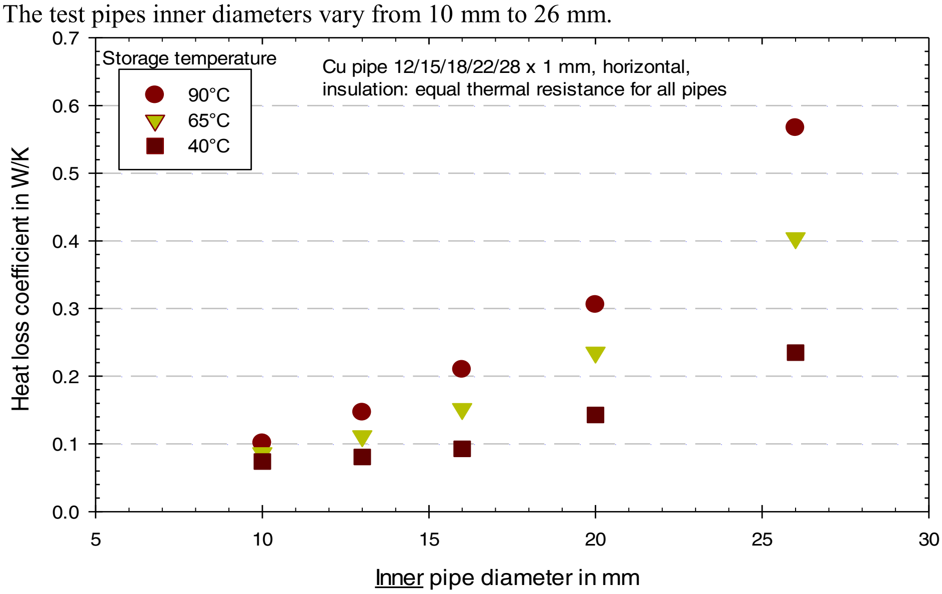

Fig. 6: Heat loss coefficients depending on storage temperature and pipe diameter of an insulated horizontal Cu pipe (wall thickness 1 mm).

Obviously, the heat losses are significantly depending on the pipe's inner diameter. Increasing the pipes diameter from 22x1 mm (20 mm inner diameter) to 28x1 mm (26 mm inner diameter) for example leads to a rise of the PIR induced heat losses of nearly 85 % for 90 °C storage temperature (65 % at 65 °C and 40 °C storage temperature). Since PIR flows in large pipe diameters experience a much lower hydraulic resistance while transporting a larger hot water volume the spread of PIR and accordingly the pipes heat losses are considerably increased. Reduced inner pipe diameters however lead to a lower intensity of the PIR induced heat losses. The longitudinal heat conduction in the tube's wall dominates the PIR induced heat losses of the installation below inner diameters of 10 mm.

3.5. Combination of horizontal and vertical pipe segments

For transferring the spread of PIR from completely horizontal or vertical orientations to a more customary combination of both cases a new procedure has been developed at ISFH. This procedure bases on the finding that the characteristic temperature profiles within a segment of the pipe are independent of the storage temperature, the temperature at the end of a first pipe segment is the relevant start temperature of a second segment. This means, that the flow momentum has no effect over a longer distance. The low flow rates (in the range of some cm per second, calculated from fig. 4) are in favor for this assumption. This property of the temperature curve allows that pipe segments may be combined to a user defined arrangement. The procedure for the prediction of composed temperature profiles has been tested and validated with experiments at ISFH, the uncertainty has been determined to less than 10 % compared to the measurements.

Fig. 7 displays temperature profiles for two pipe combinations of 4 m total length each, leading to the same final point. Arrangement A is connected to a lateral storage connecting piece. It consists of three pipe segments (segments: 1 m horizontal, 1 m vertical, 2 m horizontal). Arrangement B is connected to the storage top and has been constructed with 1 m vertical and 3 m horizontal pipe segments.

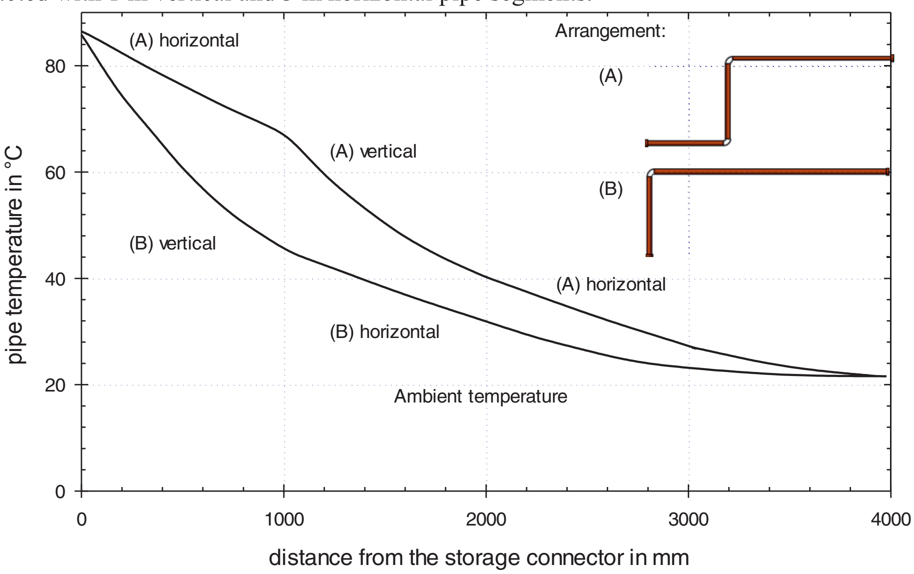

Fig. 7: Measured temperature profiles of test pipes (22x1 mm, 25 mm insulation with 0.04 W/(mK), 100 % insulation according to EnEV standard) made of horizontal and vertical pipe segments, storage temperature 90 °C

The spread of PIR and connected to that the heat losses are higher for arrangement A which is connected laterally to the storage compared to arrangement B which rises from the storage top. Furthermore, it can be derived that the characteristic temperature profiles of fully horizontal or vertical pipe segments may be detected even in segments of a combined arrangement. Because of that, temperature profiles and heat losses of arbitrary pipe arrangements can be predicted and combined basing on measurements of plain horizontal or vertical pipes.

3.6. Evaluation of PIR reducing measures

Fig. 8: Sloped storage connector in detail

The effect of different measures for the reduction of PIR induced heat losses are shown in Fig. 9. The diagram presents the heat loss coefficients for storage temperatures of 40 °C, 65 °C and 90 °C for different measures.

Heat traps like Z-profiles and slanted storage connecting pieces reduce PIR most effectively while heat traps made of CrNi are even better than those made of Cu. In case of the sloped storage connector, the impact of the increased thermal bridge inside the storage insulation has to be taken into account, too. Further results regarding different PIR reducing measures can be found in [5].

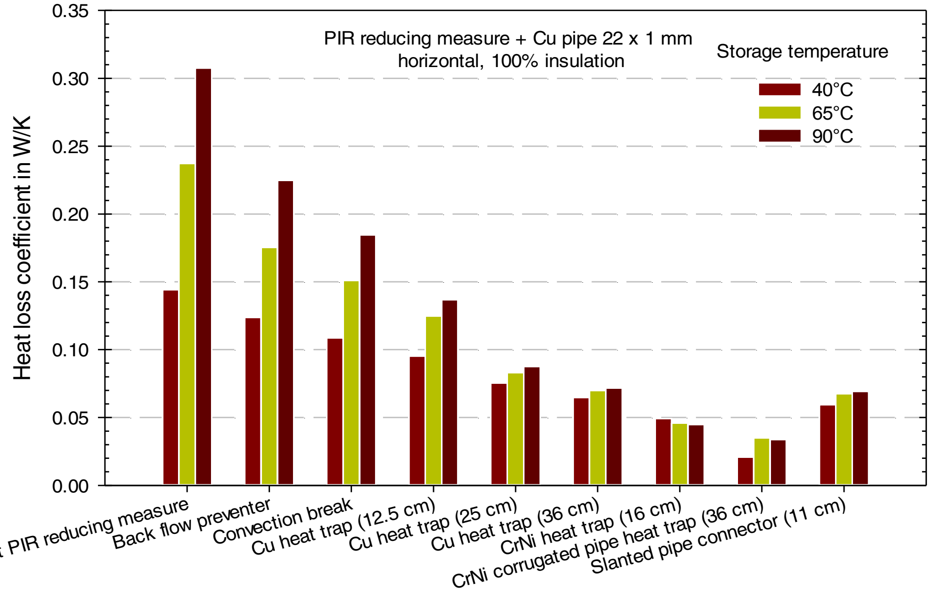

Fig. 9 Measured heat loss coefficients for pipes with different PIR reducing measures, storage temperature 40 °C, 65 °C and 90 °C

4. Conclusions

- Already slight changes of the test pipes inclination angle result in a considerable impact on the spread and, connected to that, on the amount of PIR induced heat losses. Therefore, it can be recommended to install pipes with a downward inclination of a few degrees if a heat trap cannot be installed. A positive slope has to be avoided in any case.
- The amount of PIR losses are more emphasized when using CrNi pipes due to a lower tangential thermal conduction compared to Cu pipes.
- The characteristic temperature profiles of horizontal and vertical pipe orientations remain when being joined to combined pipe arrangements. This effect allows predicting the thermal losses of real pipe installations. The calculation procedure has been proved by experiments.
- Pipe installations with a horizontal pipe connecting piece lead to higher PIR spreads and therefore higher thermal losses than pipe connections which start at the top of the storage tank.

5. Outlook

Currently, a model for the dynamic simulation of annual PIR induced additional thermal losses of different typical thermal storages is being developed, basing on the already measured variations of pipe installations. Beyond that, further pipe installations like internal and external heat exchangers will be measured and compared. Results of measurements and simulations will be compiled within a handbook for installers and component manufacturers.

Acknowledgements

The results presented within this paper are findings of a research project supported by the German “Deutsche Bundesstiftung Umwelt (DBU)” (Az. 29647). The authors are grateful for the financial support. The content of this paper is in the responsibility of the authors.

References

[1] Suter J-M. Heat losses from storage tanks: Up to 5 times higher than calculated! Industry Newsletter No. 2 from IEA SHC Task 26; September 2001, reference: http://www.solarenergi.dk/task26/downloads.html, access: 22.02.2013
[2] Andersen E. Paper X: Heat losses from pipes connected to hot water storage tanks. Technical University of Denmark, Department of Civil Enginieering, Lyngby, 2007
[3] Huhn R. Beitrag zur thermodynamischen Analyse und Bewertung von Wasserwärmespeichern in Energieumwandlungsketten. TUDpress Verlag der Wissenschaften Dresden, 2007, ISBN 978-3-940046-32-1
[4] Solar-Prüf- und Forschungszentrum Rapperswil, data collection considering PIR, SPF 2011 Rapperswil reference: http://www.solarenergy.ch/Abgeschlossen.78.0.html, acess: 29.07.2013
[5] Steinweg J, Ramin T, Rockendorf G. Investigations on storage tank losses caused by pipe internal recirculation. Eurosun 2012- ISES Europe Solar Conference, 18.09. – 20.09.2012, Rijeka, Croatia
[6] Andersen E., Paper X: Heat losses from pipes connected to hot water storage tanks. Technical University of Denmark, Department of Civil Enginieering, Lyngby, 2007