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Citation for the original published paper (version of record):

Adl-Zarrabi, B. (2018). Super insulation material in district heating pipes. IBPC 2018 Proceedings

N.B. When citing this work, cite the original published paper.

7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient
Buildings and Urban Environments

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Super insulation material in district heating pipes

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ABSTRACT

In Swedish district heating systems, 10% of the produced energy is lost at the distribution network. It is of interest to lower the energy losses both for economic and environmental reasons. Since 2011 the feasibility of using superinsulation material for insulation of the district heating pipes were studied. Apparent thermal conductivity and long term performance of vacuum panels has been identified as the crucial challenge for using vacuum insulation panels. The estimated life time of a vacuum panel in building applications at 90 °C is about 50 years. The life time estimation is based on the climate condition valid for building application. However, peak temperature in a district heating system can be about 140°C.

Hybrid insulated pipes with a Vacuum Insulated Panel (VIP) have been tested and evaluated by laboratory and field measurements. The results of numerical analyses of the measured data indicate a possible small degradation of the VIP at a similar rate as building application, even though the operative temperature is between 80-100 °C. In the laboratory a hybrid insulated pipe has withstood exposure to one sided heating at 115°C for over 5 years. The results indicate that hybrid insulated district heating pipes reduce heat losses by 20-30% for a twin pipe and with more than 50% in a single pipe. It can be concluded that VIP shows promising performance in district heating pipe applications.

KEYWORDS

Vacuum insulation panels, district heating pipe, heat losses, long-term performance

INTRODUCTION

More than 5000 district heating system are in operation within the European Union. Transferring heat and cold efficiently in urban areas is the main goal of district heating. Sweden is one of countries where more than 50% of heat demand of the building stock is covered by district heating systems. At present there are approximately 24,000 km of district heating network (DHN) in Sweden. The heat losses in DHN is 5-6 TWh (Swedish Energy Agency, 2017). There are a number of measures for reduction of heat losses e.g. a) using twin pipes instead of two single pipes, where the supply/carrier pipe and the return pipe are placed within the same insulation pipe, b) reduction of temperature level in DHN i.e. low temperature system, c) enhancing thermal properties of insulation material of the pipes.

In Nordic countries, the twin pipe concept has been used since the 1990's and utilization of low temperature district heating systems are under investigation in Sweden. However, the low temperature system was used in Denmark. Enhancing the insulation material in a DHN has been studied since the introduction of district heating systems and different types of insulations material, e.g. glass wool, mineral wool, stone wool and polyurethane (PUR), were used.

PUR is most common insulation material in new district heating pipe generation. The thermal conductivity of PUR is about 26 mW/mK at 50 °C. Research and development concerning

improving PUR insulation is ongoing. However, it is very difficult to achieve major improvements. An alternative is to replace a part of PUR insulation with Super Insulation Materials (SIM) which have 2-4 time lower thermal conductivity than PUR. Combining PUR and SIM, hybrid insulation, is the most technically feasible solution for development of high thermal performance district heating pipes.

Research related to hybrid insulation of the pipes, initiated in 2011 at Chalmers University of technology, department of Architecture and Civil engineering where a layer of SIM was added close to supply pipe. Two type of superinsulation material, aerogel blanket and vacuum insulated panels (VIP) were investigated as alternatives for hybrid insulation, see Figure 1.

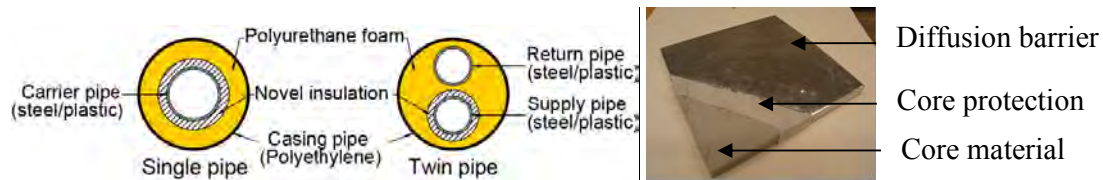


Figure 1. Hybrid insulation district heating (single/twin) pipe with VIP (left). In a VIP, the core material is enveloped by a diffusion barrier (right)

Samples and prototypes of hybrid insulation pipe were produced for investigating compatibility of SIM with polyurethane and investigating mechanical and thermal performance of the final product. Both types of selected SIM fulfilled the essential function described in (EN253, 2009). However, thermal performance of VIP was higher than aerogel blanket thus VIP was selected for further investigation.

Apparent thermal conductivity of VIP in a cylindrical geometry and expected lifetime of a VIP at a high temperature district heating network are of special interest for using VIP in district heating pipes. According to VIP manufacturer the maximum operative temperature of an ordinary VIP is about 80-90 °C which is lower than the peak temperature in a high temperature district heating system.

The aim of this paper is to present how the apparent thermal conductivity of a VIP can be determined and also present the results of analyses related to lifetime estimation of VIPs by measurement at laboratory and in operational environments.

APPARENT THERMAL CONDUCTIVITY

District heating pipes, single and twin pipe, vary in diameter thus the estimation of thermal performance of a hybrid insulated pipe with VIP needs determination of the apparent thermal conductivity of VIP for each pipe size. The thermal conductivity in the center of a VIP is declared to be between 3-5 mW/mK. To obtain the vacuum in a VIP, the core material is enveloped by an air and moisture diffusion barrier, see Figure 1, which is commonly a metalized polymer laminate or an aluminum laminate with a thermal conductivity 50-250 times higher than the center of VIP. The different thermal conductivities of the materials lead to thermal bridging effects at the edges of the panels. The linear thermal transmittance values for the edges of a plane panel can be calculated by procedures described in (ISO-102011, 2007). The influence of thermal bridges varies with the geometry of the panel, the core material and the type of diffusion barrier. The liner thermal transmittance of a number of different geometries for a plane VIP were calculated in (Sprenghard & Holm, 2014). However, the VIP in district heating pipes are cylindrical with a special formation on one surface, see Figure 3a. The non-

regular boundary between VIP and the pipe makes numerical calculation related to influence of thermal bridges on the overall thermal conductivity very difficult and uncertain. Thus, apparent thermal conductivity of VIP has been calculated in combination with measurements using the guarded hot pipe method (EN253, 2009).

The results of thermal and mechanical (fulfilling shear stress capacity caused by thermal expansions of different layers of the pipe) measurement indicates that a 10 mm thick VIP is the most reasonable thickness for a district heating pipe. Thus, the apparent thermal conductivity was determined for 10 mm thick VIP. Furthermore, manufacturing parameters related to production of a district heating pipes restrains the length of the VIP to 1 meter. The width of the panel is equal to the circumference of the supply pipe. The mounting of VIP around a supply pipe can be done in two ways 'edge to edge' or with overlapping, see Figure 3b.

Five measurements were performed for determination of steady state heat flow by the guarded hot pipe method. The first measurement, reference measurement, was performed in order to determine thermal properties of the pipe insulated by pure PUR. Two measurements were performed on hybrid insulated pipe for each mounting procedure. The pipes in the measurements were single pipe DN80/180 (supply pipe diameter/casing pipe diameter). The VIP insulation surrounding the supply pipe, see figure 1. The temperature of the supply pipe was about 80 °C and the temperature of casing pipe was about 22 °C.



Figure 2. a) Surface of a cylindrical VIP b) overlap mounting of VIP

The apparent thermal conductivity of the VIP can be calculated by using the measured heat flow and equation 1.

$$q = \frac{\Delta T}{\sum_{i=1}^N \frac{\ln\left(\frac{r_{i+1}}{r_i}\right)}{2\pi \cdot \lambda_i}} \quad (1)$$

Where q (W/m) is heat flow, ΔT (°C) is the temperature difference cross insulation material, r (m) is the radius of each layer and λ (W/mK) is thermal conductivity of each layer.

The calculated apparent thermal conductivity of a 10 mm thick VIP with a length of 1 m and a width of 0.28 m (edge-to-edge) is presented in Table 1.

Table 1: Measured heat flow and calculated thermal conductivity for the pipes and apparent thermal conductivity of VIP for two different mounting procedures.

Sample	q [W/m]	λ_{50}^{Pipe} [mW/m.K]	$\lambda_{90}^{VIP/Apparant}$ [W/m.K]
Reference	14.7	28	-
Edge-to-Edge	10.8	19	12
Overlap	9,2	17	9

The results presented in Table 1 indicate that the thermal performance of the hybrid insulated pipe is 30-60% better than the reference pipe. However, it should be mentioned that the thermal conductivity of PUR insulation in this test is higher than ordinary PUR insulation. One reason is that the PUR in these measurements are handmade. In further investigations overlapping the edges of the VIP will be used. Furthermore, apparent thermal property of VIP was about 9 mW/mK which will be used for calculation of thermal performance of single and twin pipes.

LIFETIME ESTIMATION OF VIP

The hybrid insulation of the pipes was based on replacing 10-20 mm of PUR by VIP. As long as the VIP is not penetrated the thermal performance of the hybrid pipe will be better than a pipe insulated by pure PUR: If the VIP is penetrated for any reason, aging or damaged during production, then thermal conductivity of VIP will be around 21 mW/mK which is still better than thermal conductivity of PUR. Thus, the pipe will still fulfil its thermal performance.

According to manufacturer of VIP the maximum operating temperature of a VIP is around 80-90 °C. However, the declared values are based on laboratory measurements when all sides of a VIP is exposed to uniform temperature level. In a pipe the temperature will not be evenly distributed throughout the cross section of the insulation, but will rather form a gradient. Thus, laboratory and field tests concerning lifetime estimation of a hybrid insulated pipe and related temperature levels were initiated in 2012.

Laboratory test

The laboratory test was initiated at the end of 2012 and it is still ongoing. The tests were designed for mean temperature of 90°C over cross section of VIP in a hybrid insulated pipes (80/180) i.e. a supply pipe temperature of 115 °C and backside temperature of VIP 65°C. A hypothesis is that the sealing of the VIP envelope is the weak point of the diffusion barrier. Thus, the joints (sealing in a VIP) were folded around the edge making the distance to the service pipe as long as possible. Temperature gauges were installed inside the pipe, on backside of the VIP (center part) and on the service pipe, and on the casing pipe.

Using measured data and equation 2 make it possible to find a relation between thermal conductivity of PUR and thermal conductivity of VIP. Assuming that the ageing of PUR is negligible, it is possible to indicate the changes in thermal conductivity of the VIP.

$$\frac{\lambda_{PUR}}{\lambda_{VIP}} = \frac{\Delta T_{VIP}}{\Delta T_{PUR}} \cdot \frac{\ln(\Delta r_{PUR}/r_{0,PUR} + 1)}{\ln(\Delta r_{VIP}/r_{0,VIP} + 1)} \quad (2)$$

Where ΔT_{VIP} and ΔT_{PUR} are temperature gradients over the cross section of VIP and PUR, Δr_{VIP} and Δr_{PUR} are thickness of VIP and PUR respectively. $r_{0,VIP}$ and $r_{0,PUR}$ are internal radius of VIP and PUR in a cylindrical coordinate system.

The supply pipe temperature was controlled to be 115 ± 3 °C. The ambient temperature in laboratory varied between 21 and 27 °C. The measured results of five last years (2013-2015) were analyzed in order to determine a time dependent degradation coefficient for thermal conductivity of VIP. The results of the analyses are presented in figure 3. A decrease of the ratio indicates that the thermal conductivity of VIP increases.

The ratio is decreased during the first 13 weeks and between weeks 13-78 the ratio is stable around a mean value of 3.95. This means that the VIP has a thermal conductivity which is about 4 times better than PUR. The mean temperature of PUR is about 40°C, thermal conductivity of

PUR at 40 °C is about 27 mW/mK thus the center of VIP has a thermal conductivity of about 7 mW/mK in this setup.

A failure in the devices which maintain the supply pipe temperature lead to losing data for a number of weeks, see figure 3. The failure has no influence on the pipes and thermocouples. The measurements started again at week 86. The mean value of the ratio between week 86 to 260 is 4.25 i.e. 7% higher than the ratio before failure. There is no reasonable explanation for the increasing ratio before and after failure.

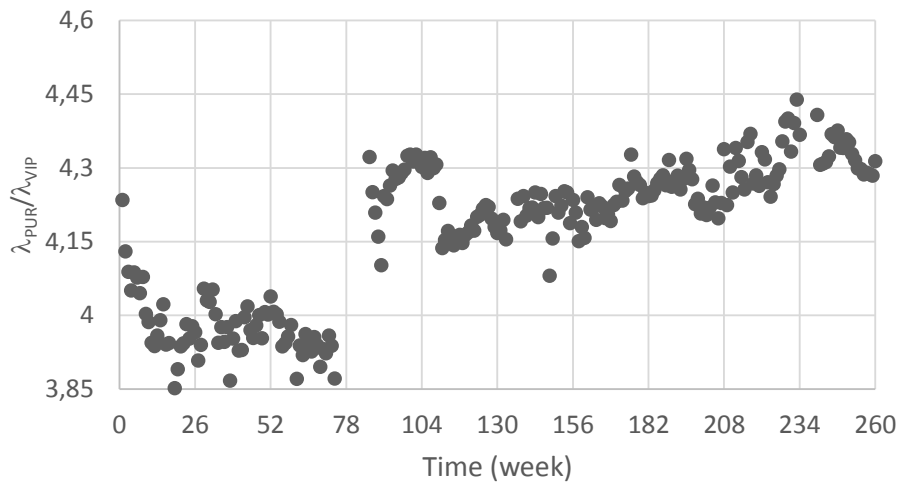


Figure 3. Variation of the ratio of thermal conductivity PUR and VIP in time.

There is a slight increase of the ratio observed between weeks 112 to 260, see figure 3. It is expected that both VIP and PUR will be degrade. It is difficult to determine the level of the degradation in each material. However, the results indicate a faster degradation of PUR than VIP.

Field measurement

Performance of the hybrid insulated pipes should be investigated in an operational environment. In field measurements the boundary condition of the pipes are quite different compared to laboratory tests i.e. the pipes lay about 1 meter below ground surface and they can be exposed to ground water flow. Furthermore, the pipes in the field station are generally twin pipes. The boundary conditions and the type of the pipes increases the complexity of analysing thermal performance of the hybrid insulated pipes.

Since 2013 five field stations were initiated in Sweden. The total length of pipe in each station is 6 meter. The pipe was divided in two parts, hybrid insulated pipe (3m) and reference pipe insulated by pure PUR (3m). The thickness and length of VIP were 10 mm and 1 meter. The VIP insulation enclosed the supply pipe. The size of the twin pipe was matched to size of the pipe in DHN. A number of thermocouples were imbedded in both parts of the pipe and on the casing pipe. The thermocouples in the reference pipe were placed in positions that they can be compared to the hybrid insulated pipe i.e. thermocouples S-VIP and S-PUR, see figure 4.

The temperature of the supply pipe follows the temperature level of DHN in the area. The results obtained from field measurement were used for validation of a numerical model. The numerical model and the results based on measurements during 2013-2016 were presented in (Berge,

Hagentoft, & Adl-Zarrabi, 2016) and (Berge A. & Adl-Zarrabi, 2014). The results of the numerical analyses showed that a total reduction in the energy loss between 20% and 30% compared to pipes of the same size with pure PUR insulation. Furthermore, the losses from the supply pipe decreased by up to 56%

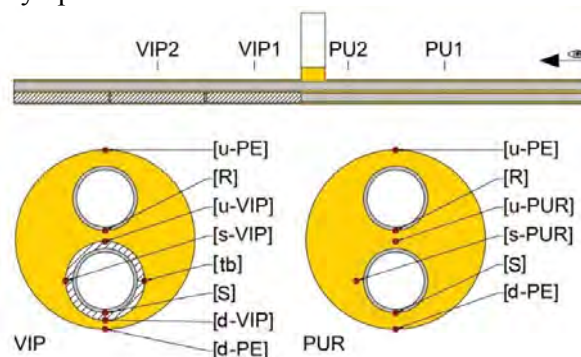


Figure 4 Position of VIP (dashed lines) and thermocouples in the twin pipe. PU1, PU2, VIP1 and VIP 2 sections where thermocouple positions were mounted.

The simulations also show that a slower deterioration process could be hidden in the responses to other variations in the system (Berge et al., 2016). The measured results during 2017-2018 were analysed and the results supported the same conclusions as presented in 2016.

CONCLUSIONS

The apparent thermal conductivity of a VIP in district heating pipes varies with dimension and type of the pipe. The apparent thermal conductivity of a 10 mm thick VIP at 50 °C used for insulation of a 40 mm supply pipe is about 9 mW/mK which can be used as a benchmark. Hybrid insulated district heating pipes reduce the heat losses by 20-30% for a twin pipe and by more than 50% in a single pipe. The results of field measurements show that hybrid insulated pipes using VIP fulfil their function after five years in an operational environment. Thus, hybrid insulated pipes by VIP have potential to improve long-term thermal performance of the district heating network.

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