TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

Diploma Project

Test system design and measurements of the thermal conductivity for composite pipes

Carried out at the
Institute of Applied Physics

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1 Summary

This project focuses on the development of a testing system for plastic jacket pipes and the change of thermal conductivity λ due to aging effects in the insulation material. The study at hand utilizes in contrast to the majority of existing publications only naturally aged specimens to eliminate the uncertainties of the artificial aging process.
Both main objectives of this study are fulfilled: on the one hand a cost efficient (material costs below EUR 4.000) and reliable measurement system to determine the thermal conductivity of insulation layers in compound pipes was developed. On the other hand unused and used plastic jacket pipes in various states were measured to study the change of thermal conductivity due to aging effects in the insulation material for PUR closed-cell foams.

A well designed system was devised to maximize measurement accuracy (resolution $< 0.3\,°C$) and ease of operation. The samples can be changed easily and require minimal preparation effort. The measurement system uses thermal equilibrium of the sample pipe with an ambient air volume and heating power monitoring to calculate the thermal conductivity of the insulation layer. A balanced combination of hard- and software components as well as computer simulations save man hours and energy consumption. The samples are mounted on two support holders in a temperature controlled environment. A control unit regulates the heating and cooling elements. A data acquisition unit converts the electric sensor signals into serial data. The samples are filled with a fluid and heated by a central heating rod. Temperature sensors on the surface and within the pipe combined with geometric specimen dimensions and known material properties permit the calculation of the thermal conductivity. Finite element models were used to determine the influence on the calculations and magnitude of convection, thermal radiation and heat flux.

The gained data confirms general trends of previous studies concerning the aging effects on thermal conductivity of plastic jacket pipes used in district heating systems. Thermal conduction measured for unused pipes is $\leq 0.0270\,W/(m\,K)$ as defined by the producing companies and $< 0.0290\,W/(m\,K)$ as governed by the European standard EN 253 for new pipes.
Unused pipes after 5 years of storage show similar values thus confirming the product stability concerning the effect of prolonged storage on the thermal conductivity. The used sample pipes showed that even after prolonged operation of more than 20 years at usual temperatures in the range of $80\,°C$ to $90\,°C$ only small relative increases in thermal conductivity $< 10\,\%$ can be detected.
This results indicate a significantly smaller deterioration of the insulation properties than former studies with artificially aged pipes stated.

2 Measurement System

A variety of factors have to be considered for a successful design of a measurement system, such as e.g. the most suitable time constant, amount of available funds, sensor type, means of measuring surface temperatures, data acquisition layout and operation. Many of these aspects for choosing a temperature measuring system are listed in the *Handbook of Heat Transfer* [4, p.16.55 f]. To gain representative sample pipe sections a detailed specimen specification defining the length, diameters and cell gas was issued. This simplifies the development of a suitable measurement system and ensures good comparability between different times of operation and mean operation temperatures.

2.1 Hardware Components

2.1.1 Specimen Mounted Components

The specimens are capped by two circular flanges made from stainless steel with an sealing ring fastened by four thread bars. Both sides are identically designed. On one side an ohmic heating element is screwed into the flange along the center axis. On the other side a pressure relief valve is mounted to act as an automatic fail safe. At each flange a copper pipe protects the Pt-100 sensors measuring the fluid temperature inside the specimen. Planar grooves on the inner side of the flanges ease the necessary alignment for pressure tightness. Outer specimen diameters up to 160 mm can be accommodated. To minimize heat losses at the flanges two types of insulation were used: insulating caps made from polyurethane foam and an EPDM rubber ring for the inner sides of the flanges protruding the outer specimen diameter.

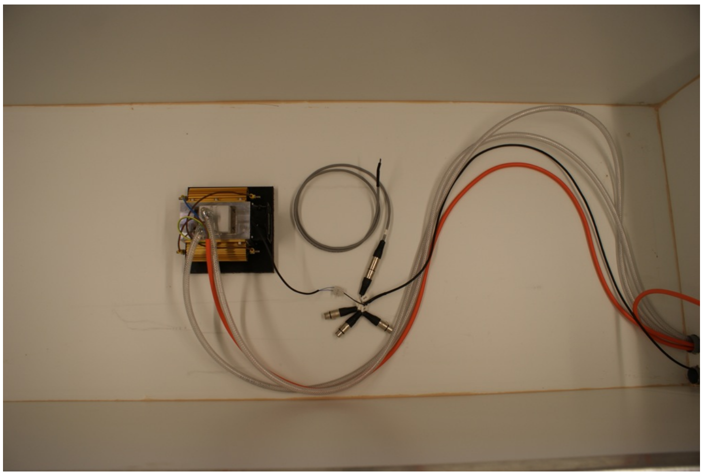
The Pt-100 sensors measuring the outer surface temperature of the specimen are fixed with four thin sheet steel collars. Stainless steel in a thickness of 0.8 mm was chosen for the collars because of the potentially wet surroundings and the relatively small minimum bending radius of $\approx$ 62.5 mm.

Two specimen supports with a v-shaped notch are used to position the specimen in the enclosure. The notch shape and the material (PEHD slates with 10 mm thickness) were chosen to minimize heat flow through contact surfaces.

2.1.2 Specimen Enclosure

The specimen enclosure was build from insulation panels consisting of three layers: two thin sheet metal plates and a hard foam insulation in between. It was designed for the main tasks of keeping the air around the specimen thermally insulated from

(a) Basis enclosure



(b) Enclosure with heating / cooling block

Figure 1: Specimen housing

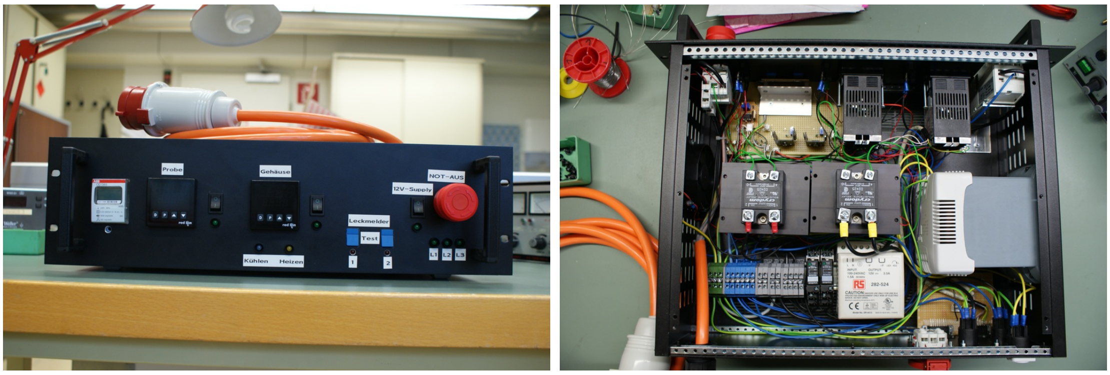
the surrounding air and to prevent undesired air flow. Two feedthroughs were installed to allow easy access into the housing for necessary cables and tubes. To condition the air temperature in the enclosure a heating and cooling block was added. It consists of two heating elements and a cooling heat sink mounted on a common string heat sink. Air is blown through the fins of the common heat sink with a fan.
Fig.2 shows a top view of a fully assembled sample in the specimen enclosure ready for measurement.

2.1.3 Control Components

A 19 inch housing holds the control components. A three phase mains connection is used to reduce electromagnetic noise in the whole system (e.g. caused by valves, relays and motors). In the back section a DIN cap rail is installed for the various power distribution elements and a 12 V power supply for the electronic circuits. Self locking connectors were used for all critical power lines. An isolated ground receptacle was integrated for the data acquisition (DAQ) module mains supply. A 15 line multicore cable connects all necessary sensors and control lines with the specimen enclosure. An other multicore of the same dimension connects the control with the data acquisition unit.

A PID controller in combination with three solid state relays is used to regulate and monitor the air temperature in the specimen enclosure.
The second PID controller switches a solid state relay which is connected through

Figure 2: Specimen enclosure top view with mounted sample



(a) Front view

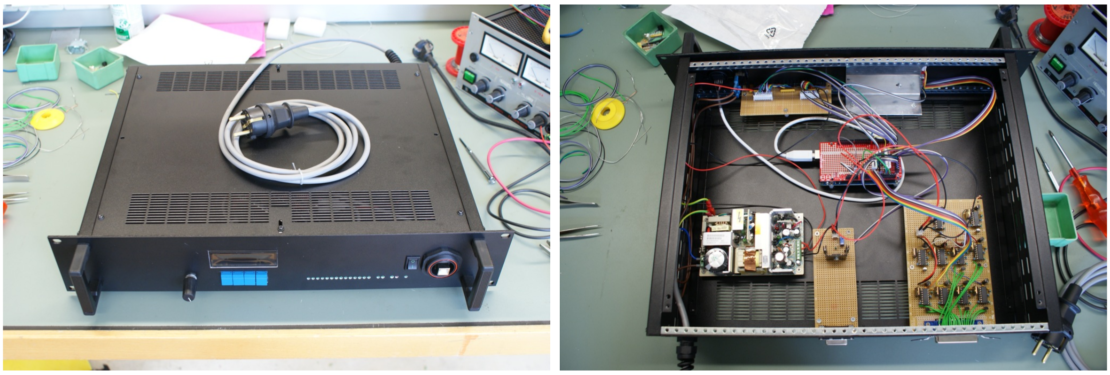
(b) Top view

Figure 3: Finished Control Unit

the energy meter to the heating element inside the specimen to heat the fluid. The energy meter sends one pulse for every 1 W h detected to the DAQ unit.

An emergency stop push-button disconnects all supply lines including the cooling water if activated. A temperature controlled fan keeps the various heat sinks of the electronic components cool if the temperature rises above an adjustable level. The power supplies of the PID controllers and the remaining circuits can be switched on individually. A leakage detection circuit with two red LED indicators shows if there is a spill in the specimen enclosure.

2.1.4 Data Acquisition Components



(a) Front view (b) Top view

Figure 4: Finished Data Acquisition Unit

A 19 inch housing holds the data acquisition components together with a switch-mode power supply for the circuit boards. A reference voltage source was added to ensure reliable measurements. On the preprocessing circuit board ten 4 mA to 20 mA current transmitter chips with integrated linearization for Pt-100 elements are mounted to convert the resistance differences to current differences. Those are transformed into a voltage signal by high accuracy resistors with low temperature drift.
Two sensor types were used in the system: Pt-100 resistive sensors and semiconductor temperature-to-voltage converter. All sensors are connected to the processing circuit board via shielded cables through a multicore cable.

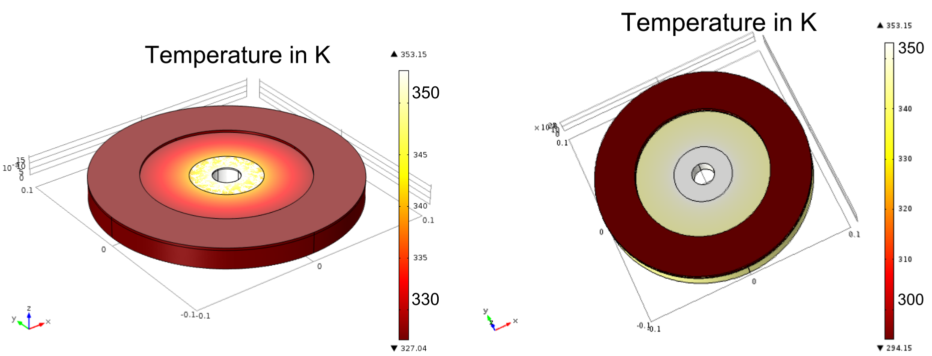
An Arduino board is the heart of the data acquisition electronics. For the data connection a robust USB receptacle in the front grants access to the microcontroller board via a virtual serial port. For good usability a LCD display, LEDs and buttons were installed to view sensor readings. A 10-bit analog to digital converter (ADC) combined with the reference voltage source achieve a resolution of less than 0.5 mV per ADC step. This implies a resolution below 0.3 °C with an error of $\leq 1.1\,\%$ for the current transmitter chips with Pt-100 circuits. Furthermore, less than 0.5 °C resolution with an accuracy of typical ± 0.5 °C (max.± 2 °C for $T \leq 85\,°C$) for the semiconductor sensors.

2.2 Software Components

The programming code on the microcontroller board manages the user interface, raw data conversion and transmission via a virtual serial port. The data analysis software uses the Matlab environment to achieve the following tasks: data read in from the DAQ unit, graphical display of datasets, calculate the heat conductivity λ and execute automated evaluation of multiple measurements.

2.2.1 Finite element model

A three dimensional and an axis-symmetric two dimensional model for a finite element simulation was created to determine the heat losses through the flanges. Due to the convection calculation results a natural convection mechanism combined with heat transfer in solids was chosen. Fig.5b shows the significant heat flux decrease with a rubber ring covering the surface area otherwise left uninsulated. The reduced heat loss is indicated by the brighter colors in the area inside of the ring.



(a) Temperature distribution of flange B (b) Temperature distribution of flange B with an added rubber insulation

Figure 5: COMSOL Multiphysics 3D model of heat transfer in the flanges

More detailed geometric models for each of the used pipe types were used to generate the corresponding heat flux data sets for the lambda calculation.

3 Measurements

The chosen samples are presented in Tab.1 together with the corresponding measurement results. The deviations of the collected data sets can be described by a Gaussian distribution. Therefore, the given range of $\pm 1\sigma_{mean}$ around the mean value include 68.27 % of all possible values (according to general probability calculations).

Table 1: Specimen Overview

Nr.	ID	Size	Age $[years]$	λ_{mean} $[W/m \cdot K]$	σ_{mean} [%]
1	isop.ref1	DN50 / 125	0 (new product)	0,0246	6,9
2	isop.ref2	DN50 / 125	0 (new product)	0,0269 [a]	6,3
3	linz.kel1	DN50 / 125	0 (new product)	0,0230	9,7
4	linz.kel2	DN50 / 125	0 (new product)	0,0259	4,6
5	isop.alt1	DN50 / 125	5 (in storage)	0,0271	5,1
6	isop.alt2	DN50 / 125	5 (in storage)	0,0239	7,4
7	sten.iso1	DN50 / 140	24 (used at 80°C)	0,0295	3,6
8	isop.ref5	DN50 / 140	0 (new product)	0,0269 [a]	4,8
9	enag.pvc1	DN50 / 160	35 (used at 90°C)	0,0289	4,5
10	isop.ref6	DN50 / 160	0 (new product)	0,0265 [a]	4,0

[a] Calibration specimen

The first group of specimens (Tab.1 Nr.1 to 6) are unused compound pipes fulfilling current standards which were produced only weeks before testing. The next group are unused pipes (Tab.1 Nr.7 to 8) with a production date in the year 2007 to investigate the aging process under storage conditions. The last group of specimens (Tab.1 Nr.9 to 10) consists of two pipes after long-term operation and unused counterparts for referencing purposes.

Used and unused specimens were tested in order to answer the key questions of changing heat conductivity for closed cell foam PUR insulation materials. The measurement setup was designed for complete compound pipe sections to minimize the risk of damaging the test pieces due to complicated specimen preparation.

To reach the desired data quality of the results several factors have to be considered. On the one hand statistical fluctuations are compensated by taking the average value of lambda for multiple measurements and electronic noise is reduced in the analysis software by an filtering algorithm. On the other hand to minimize deviations due to system characteristics (e.g. differences between idealistic computer model and real system) a reference measurement was conducted. A set of Pt100 sensors (one sensor for each DAQ input channel) together with a calibrated temperature probe were fixed onto an aluminium block submerged an ice water bath. The results showed only minimal deviations between the individual channels of less than 0.05 °C.

The heat losses through the flanges are calculated using a two dimensional computer simulation and compensation factors gained by tests of reference specimens. For a desired fluid temperature of 80 °C and an ambient air temperature of 23 °C, the calculated heat flux through both flanges adds up to $\approx$ 18 W.

To prove the reproducibility of measurements a second reference specimen was tested and repeated measurements showed only small deviations. To validate the used computer model and the referencing method a validation specimen with the same properties as the reference sample was tested. The resulting data is compared in Fig.6. The difference of the shown mean values for specimens of $\approx$ 4.5 % is within an acceptable range. No significant drift across multiple measurement series was detected. Relative result deviation seems to be random as the distribution of deviations is similar to a discrete uniform distribution.

3.1 Result Overview

The results of all measurements are depicted in Fig.7. For easier separation of the different specimen classes the error bars are color coded: Green for new samples, orange for unused specimens after prolonged storage and red for specimens after more than 20 years of usage. The age in years of each specimen is shown in the legend at the lower right corner of Fig.7.

3.2 Interpretation

The gained data confirms the tendencies discovered by previous studies concerning the aging effects on thermal conductibility of plastic jacket pipes (e.g. [3]). However, in this study several interesting observations were made regarding the mea-

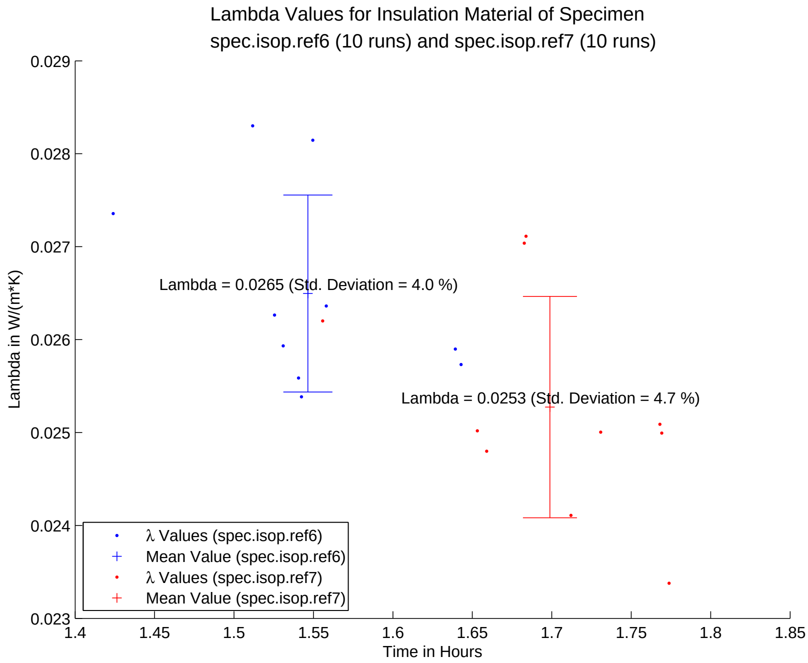


Figure 6: Plot of a reference and validation specimen

surement results. The first four specimens (isop_ref1, isop_ref2, linz_kel1, linz_kel2) are unused DN 50/125 pipes directly taken from two different producers. They show a similar scattering with mean values of $\lambda \approx 0.0258\,\mathrm{W/(m\,K)}$, $\Delta\lambda \lesssim 9\,\%$ and $\lambda \approx 0.0245\,\mathrm{W/(m\,K)}$, $\Delta\lambda \lesssim 12\,\%$. Their absolute mean values for the heat conductibility λ are within and below the upper limit of $\lambda \leq 0.0270\,\mathrm{W/(m\,K)}$ defined by the producing companies. Moreover, they are well below the upper limit of $\lambda \leq 0.0290\,\mathrm{W/(m\,K)}$ governed by the European standard EN 253 [2, p.18] for new pipes.
The next two specimens (isop_alt1, isop_alt2) are unused pipes after 5 years of storage. They show no significant change compared to the first four samples and confirm the product stability concerning the effect of prolonged storage on λ.
Although the duration of operation for sample enag_pvc1 amounts to 35 years its relative increase in λ of $\lesssim 9\,\%$ is smaller than the relative increase of $\lesssim 10\,\%$ for specimen sten_iso1 with 24 years. This leads to the deduction that larger insulation layer thickness decelerates overall thermal ageing. An other conclusion of these last four measurement results is: even after prolonged usage at conventional operation temperatures in the range of 80 °C to 90 °C only small relative increases in λ of $\lesssim 10\,\%$ were detected. This result is significantly smaller than anticipated based on former studies but it is in accordance with the findings of another recent study [1, p.84ff].

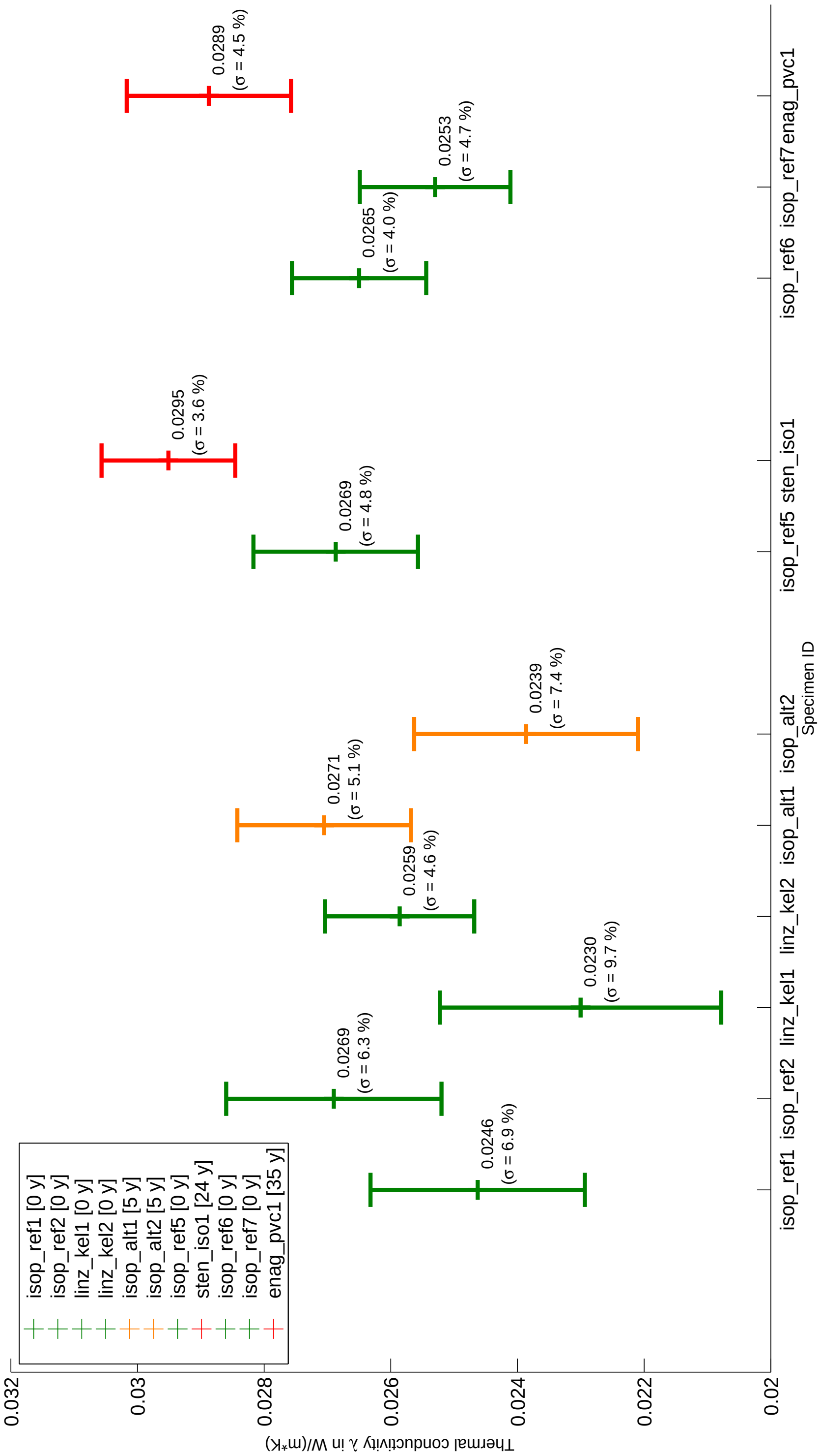


Figure 7: Result Overview

4 References

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